

**A STUDY OF HUMAN-ROBOT INTERACTION WITH
AN ASSISTIVE ROBOT TO HELP PEOPLE WITH
SEVERE MOTOR IMPAIRMENTS**

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A STUDY OF HUMAN-ROBOT INTERACTION WITH AN ASSISTIVE ROBOT TO HELP PEOPLE WITH SEVERE MOTOR IMPAIRMENTS

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To my family,

Sae Jin Kim, Da Hyeon Choi, and Jae Ho Choi,

and my parents, Kun Sik Choi and Ok Ja Lee.

PREFACE

During the last two years, I have considered myself to be very lucky to have met great people through my research, patients suffering from ALS and the family members who took care of them. Although I knew that most of the patients were experiencing devastating physical difficulties, I always felt happier after spending time with them due to their warmth and kindness. These people's bright minds and spirits enabled me to continue the research described in this thesis. I appreciate their kindness and will remember our shared experiences forever. Although the studies conducted in the thesis will not cure or slow the disease, I believe that affordable and effective robots will be deployed to help people suffering motor impairments. I hope the small piece of this goal represented by this thesis will help shorten the waiting time.

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SUMMARY

The thesis research aims to further the study of human-robot interaction (HRI) issues, especially regarding the development of an assistive robot designed to help individuals possessing motor impairments. In particular, individuals with amyotrophic lateral sclerosis (ALS) represent a potential user population that possess an array of motor impairment due to the progressive nature of the disease. Through review of the literature, an initial target for robotic assistance was determined to be object retrieval and delivery tasks to aid with dropped or otherwise unreachable objects, which represent a common and significant difficulty for individuals with limited motor capabilities. This thesis research has been conducted as part of a larger, collaborative project between the Georgia Institute of Technology and Emory University. To this end, we developed and evaluated a semi-autonomous mobile healthcare service robot named EL-E. I conducted four human studies involving patients with ALS with the following objectives: 1) to investigate and better understand the practical, everyday needs and limitations of people with severe motor impairments; 2) to translate these needs into pragmatic tasks or goals to be achieved through an assistive robot and reflect these needs and limitations into the robot's design; 3) to develop practical, usable, and effective interaction mechanisms by which the impaired users can control the robot; and 4) to evaluate the performance of the robot and improve its usability.

In the initial user needs assessment, I identified the needs and wants of the target users (recruited from the ALS Center of the Emory Clinic) through user interviews and field studies involving the documentation of occurrences of object retrieval difficulty. The results help to inform the design and development of the robot system,

with respect to common objects to be retrieved, preferable methods of object return/delivery, and the acceptance of potential control interface, as well as to direct the planned evaluation activities to test the assistive robot’s abilities to meet the users’ needs. This needs assessment also led to the development and validation of a list of common objects ranked according to their relative importance in terms of user needs for activities of everyday living and, thus, potential targets for robotic-assisted retrieval. It is anticipated that this developed list of practical, meaningful objects can serve as a foundation for further research in robotic object manipulation, which currently consists of studies that ”cherry pick” objects to use for robotic system evaluation. A set of useful benchmarks to evaluate and compare developed robots and assistive technologies would help to ensure that those systems developed by researchers can have a practical impact in meeting the actual needs of the target user populations in their real world living environments.

To this end, an initial series of human evaluation studies were conducted to study two pragmatic issues - the design of a usable user control interface for users with varying motor limitations and the object delivery method of handing off a retrieved object to the human user. In the first study, three distinct user control interfaces were developed: 1) a modified, hand-held laser pointer; 2) a modified, ear-mounted laser pointer; and 3) a touch screen, graphic user interface on a portable computing device. Users were asked to utilize these control interfaces to direct the robot to the three-dimensional coordinates of a target object for the purposes of object retrieval. The empirical results illustrated a high success rate of object retrieval (94.8%) and a very high level of user satisfaction. Perhaps not surprisingly, user preferences for the control interface were highly correlated with users’ quantitatively measured motor capabilities, with upper limb mobility an important determinant of interface preference. More importantly, however, three viable control interfaces were developed to accommodate the variability in ALS patients’ motor capabilities. Additionally, the study

illustrated that the general paradigm of conveying 3D object location information to the assistive robot, regardless of the interface mechanism used, can successfully result in task completion without any required changes to the actual robot design and functionality.

The second user evaluation study examined two delivery mechanisms - direct delivery to a user's hand and indirect delivery to a nearby surface - to determine the limitations with robot-assisted object delivery. Overall, the robot successfully delivered objects with a success rate of 98% for indirect delivery and 78% for direct delivery (with an overall success rate of 88% or 126 out of 144 trials across all conditions). The results indicate that indirect object delivery, the preferred method for some users, provides a robust and reliable (albeit slightly inefficient) object delivery method. The direct object delivery method suffered from complications with the semi-autonomous robot's ability to handle the diversity of seated posture positions and body types that exist. Overall, the results from these evaluation studies suggest that ease to learn, ease to use control interfaces can be implemented, which will suit the needs of the diverse population of individuals with significant motor impairments, to control an assistive robot to safely and effectively retrieve and deliver objects to a human user (commonly using wheelchairs).

I anticipate that the findings from this research will contribute to the ongoing research in the development and evaluation of effective and affordable assistive manipulation robots, which can help to mitigate the difficulties, frustration, and lost independence experienced by individuals with significant motor impairments and improve their quality of life.

CHAPTER I

OVERVIEW

1.1 Objective of the research

The research aims to study human-robot interaction (HRI) issues relating to the development of an assistive robot, which has been designed to help individuals suffering from motor impairments - especially those with amyotrophic lateral sclerosis (ALS) - with everyday object retrieval tasks. This research has been conducted as part of a larger, collaborative project between the Georgia Institute of Technology and Emory University. This project was initiated to develop an assistive robot that can aid individuals possessing severe motor impairments with fetching everyday objects that have been dropped or are otherwise unreachable. Specifically, the research consists of: 1) a user needs assessment using interview and observation, 2) creation and validation of a list of practical, everyday objects that are meaningful to potential end users, 3) the development of human-robot interface technologies to allow the user to control the robot, and 4) user evaluation studies of the interaction between these prospective users and the assistive robot. This thesis work is based on the following objectives:

1. To investigate the needs of users with motor impairments:

In order to develop a robot suited for the target population, a user needs assessment was conducted to gather information on what users need and want from an assistive robot.

2. To reflect the needs of these users in the robot design:

The wants and needs of users, identified in the initial assessment, was used to determine the design requirements and choose among design alternatives during

the development process of the assistive robot.

3. To evaluate and improve the usability of the assistive robot:

Evaluation of the robot system utilized a formal user testing method with controlled lab-based empirical studies to determine that the implemented technologies are able to achieve an acceptable level of performances with respect to speed, accuracy, learning time, and subjective user satisfaction. Through the evaluation studies, we also sought to discover any potential accessibility and usability problems and derive solutions to these problems.

4. To develop and evaluate a human-robot interaction mechanism:

Around the time when these research efforts began, a point-and-click interface, using a standard hand-held laser pointer, was suggested as the primary interaction mechanism for the assistive robot. In addition to the evaluation of this interaction mechanism, we also aimed to design and develop alternative interfaces such as ear-mounted laser pointer, touch screen graphical user interface, and redesigned hand-held laser pointer suitable for use by this target population who possess, sometimes significantly, limited motor and dexterity capabilities. We also wanted to study possible alternative methods of fetching and delivering objects.

1.2 Motivation

Although many people take it for granted that they possess the physical capabilities to perform tasks of daily living, such as picking up and holding an object, these tasks present significant and sometimes life-threatening challenges for individuals with limited motor capabilities. A survey by the U.S. Census Bureau [90] recently reported that more than four million Americans (1.56% of the total population) possess some

kind of physical disability that hinders basic physical activities such as walking, climbing stairs, and reaching, lifting, or carrying objects. The terms "physical disability" and "motor impairment" are sometimes used interchangeably, although the term motor impairment will be used throughout this work. Survey results show that as individuals grow older, the percentage of those with impairments grows steeply. For example, 42.96% of Americans older than 65 had physical disability while 1.56% of whole population had. Elderly individuals tend to have more motor impairments due to the prevalence of disease and other natural consequences of aging.

In addition to the effects of aging, there are other specific causes of motor impairment which can affect people, regardless of age. Physical injury and neurological disease are two primary causes of motor impairments. Injuries such as car accidents and war wounds can harm the human musculo-skeletal system. While amputation of limbs affects specific body parts, neuronal injuries such as spinal cord injuries can have wider-reaching effects on mobility. Quadriplegics cannot move their arms or legs because spinal cord damage has impaired the communication channel between the brain and the limbs. As different injuries affect various parts of human body to varying degrees, there are no simple, universal solutions to provide assistance to those individuals with motor impairment.

While physical injuries affect human mobility from outside of the body, neurological diseases harm from the inside. Because humans can only move their voluntary muscles when their brains send commands through the nervous system, malfunction of this communication can decrease human mobility without any wounds or injury. Amyotrophic lateral sclerosis (ALS), also known as Lou Gehrig's disease, is a very severe neurological disease. ALS affects the whole human body in progressive fashion. In comparison to injury-related motor impairment, ALS patients experience increasingly progressive motor impairment, until death. The disease severity and progressive nature of ALS prompted the choice of this population as the prospective users of an

assistive robot. Even though the assistive robot cannot cure or slow the progress of ALS symptoms, the assistance provided by the robot could increase these individuals' quality of life. In addition, the help provided by the robot may help mitigate some of the daily troubles and frustration experienced by those with ALS and their caregivers. In addition, the progressive nature of the disease would be useful to validate the usefulness and adaptability of the developed robot to other types of motor impairment, as the robot must fulfill the requirements of various levels of physical impairments experienced by patients with different phases of ALS.

One of the most significant problems individuals with motor impairment experience is loss of independence. Individuals who cannot move both arms freely have difficulty in daily tasks such as washing, eating, opening doors, and so on. Individuals who cannot stand up and walk, have difficulty with moving from place to place, but can find help with wheelchairs. However, although individuals in wheelchairs achieve some relative independence in movement, they have difficulty when an object is dropped on the floor or placed on a shelf out of reach. Assistance with object retrieval is one of the tasks anticipated to be of help to individuals with motor impairment [82]. The loss of independence experienced by individuals with motor impairments requires outside help. Human caregivers are possibly the most helpful, but also most expensive solution. Hospitals and care facilities provide limited services by nurses and other supporting staff. However, the cost of these specialized services is continually becoming more expensive. People living in their own homes need caregivers staying with them. However, hiring professional caregivers is also very expensive and can be alienating to patients. If family members are required to help, then it prevents them from working and having enough time for their own daily chores and lives.

Due to the expense and difficulty of finding human assistance, helper animals have been sought to aid people with lost independence. Helping Hands is a non-profit

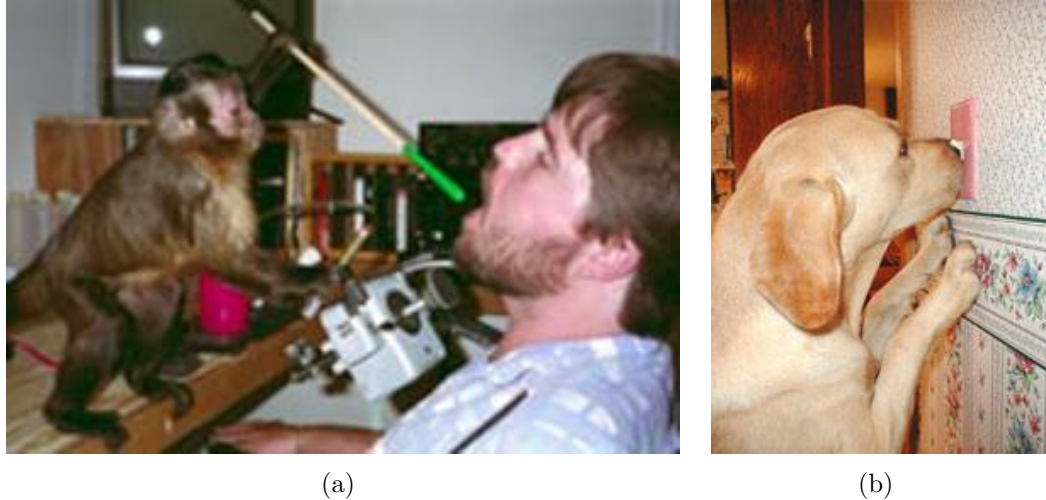


Figure 1: (a) Helper monkey [33] (b) Service dog [27]

organization that trains monkeys and makes them available to help individuals with disabilities such as spinal cord injuries [33]. Because monkeys have higher intellectual capabilities than other animals, they are capable of performing various tasks that are helpful to humans with motor impairments (see Figure 1.2). For example, a monkey can pick up and retrieve an object following direction from a user by a laser pointer.

In addition to monkeys, dogs have also been used to help individuals with impairments (see Figure 1.2). Georgia Canines for Independence provides highly trained service dogs to people with disabilities [27]. One of the services provided by the society is “mobility service dogs”, which trains canines to learn approximately 80 commands designed to help children and people with physical disabilities. These dogs can help people with opening and closing doors, turning on and off lights, or retrieving dropped objects. Although these animals are very helpful, it takes a long time and high cost to train these animals. The time and cost of training, as well as the short lifespan of the dogs, is why the demands for these services greatly exceeds the supply from these organizations.

Devices such as cars and computers have been created for various purposes of efficiency, support, and convenience. To help individuals with motor impairments,

robots can easily be perceived to be of use without requiring much imagination. A robot is a machine that can be reprogrammed for various tasks. From the inception of the term in a Czech play, R.U.R, in 1921 [7], robots have been imagined as human-like machines that can do almost all things humans can do. The ideal robot would be able to listen and understand when a human user speaks and to make decisions on what task or action is required. However, despite the research and advances in robotics, the full-fledged humanoid robot with human-like cognitive and motor capabilities is still merely a dream. Therefore, task-specific technologies need to be developed and tested for specific situations or contexts. True assistance of individuals with motor impairments requires that an array of tasks be aided, although complete assistance cannot be robustly achieved by current robot technologies. Therefore, this research suggested an approach to focus on a task, representing an urgent need, which can feasibly be achieved with state-of-the-art technology. The assistive robot developed in this project focussed on the task of retrieving objects for users with significant, although varying, motor impairment.

In order to fully explore the universal needs associated with object retrieval, I investigated previous research efforts on robotic object manipulation assistance. The wheelchair-mounted robotic arm is one of the solutions developed so far. The Assistive Robotic Manipulator, known as MANUS, is a commercially-available, wheelchair-mounted robotic arm [53]. It can help individuals with various tasks, not limited to just object retrieval. MANUS can be controlled by joystick and keypad. Thus, despite the usefulness of the robot, using the controllers presents a challenge for those with severe motor impairments. The direct tele-operation of this kind of robotic device is often difficult even for the able-bodied. Autonomous robotic systems with manipulation capabilities can be very helpful in situations where users have motor impairments. The assistive robot system developed in this research is expected to help users with motor impairments achieve limited autonomy in object retrieval tasks.

Although technical advancements in robotic technologies have great potential for helping people with motor impairments, the application of the technology should be accompanied by a study of the human component of the system, such as users possessing motor impairments. Varying degrees of impairment to an array of body parts makes it difficult to design a specific technological solution that can be applied to all potential users. Moreover, because the robots will be operated in different environments, including hospitals, nursing homes, or users' homes, the variability present within physical environments (e.g., the physical structure of residence, lighting levels, and the activities of other humans in the environment) should also be considered. This thesis research focussed on these human elements and their interaction with robot technologies via an assessment of actual user needs and investigation of prospective operating environments through site visitation and photographing. Further involving prospective users in evaluation studies revealed potential accessibility and usability problems of the developed assistive robot.

1.3 General background

In this section, I discuss previous research accomplishments in the area of assistive robotics and human robot interaction in order to frame the context of the presented thesis work. In the following chapters, which discuss the human studies performed in this thesis work, additional literature specifically related to the specific studies are discussed in the related works section of each chapter.

1.3.1 Robots and human-robot interaction

A robot can be loosely defined as a “re-programmable multi-functional manipulator” [28] although there are several conflicting, detailed definitions. Re-programmability distinguishes robots from other automatic machines. From the inception of the term by a playwright, people have conceived robots as human-like machines which can think and move just like human beings. However, the first commercial application of

robots did not look much like humans. From the 1960s, when they were first introduced by General Motors to an automobile assembly plant [28], industrial robots were developed and widely installed in manufacturing facilities all over the world. In most cases, these industrial robots were placed in a confined area of the factory floor and performed pre-defined, albeit re-programmable, material handling and manipulation tasks. Although these robots have re-programmability, they are controlled in a similar manner to other industrial equipment, such as computerized numerical control machines or unmanned guided vehicles. The rapid progress of digital computer and communication technologies brought about the era of intelligent robots, which have advanced computing power compared with traditional industrial robots. Because intelligent robots can accomplish complex and varied tasks, the role of human control over the robot also dramatically increased. With the advent of intelligent robots, human-robot interaction has gained importance as a research topic. This interaction has been deemed necessary to design and build effective robot systems which include human users.

1.3.2 Taxonomies of HRI

Human-robot interaction studies are closely related with human-computer interaction, as most modern robotic systems employ hardware and software components used in other common computing systems. However, the peculiarity of human-robot interaction, in comparison to other areas of human-computer interaction, is that the robot interacts with the world and is in physical contact with the human operator. Human-computer interaction primarily deals with user interface technologies, such as keyboard and mouse input devices and visual/auditory interfaces, which human operators use. However, this physical interaction is confined to input and output activities used to support the completion of computer-based tasks. In comparison with virtual world-based personal computers, robots exist in the real world. This

Table 1: Dimensions of robot taxonomies

Dimensions	Components	Examples
Application Areas	Industrial robots Service robots	Assembly and transport robots Home/office service robots, rehabilitation/healthcare robots
Autonomy	Fully autonomous Semi autonomous Non-autonomous	Humanoid robots with ideal artificial intelligence (Note: non-existing yet) Most currently available robots Tele-operated robots
Mobility	Mobile robots Stationary robots	Robots on vehicles (e.g., Mars Exploration Rover), walking robots Fixed manipulators (e.g., MANUS arm, stationary assembly robots)

actual physical existence creates potential problems with safety, as well as physical constraints created by human bodies. The sensory and motor abilities of humans, as well as their limitations, pose a greater challenge for human-robot interaction than in other human-computer interaction areas. These challenges become even more apparent when robots are developed for users with sensory and/or motor impairments.

Various types of robots exist, making human interaction with these robots a variable problem. Thus, it would be useful to produce some form of taxonomy to compare existing and future applications of human-robot interaction within a unified frame of reference. Yanco and Drury [103] compiled various attempts of creating taxonomies of human-robot interaction, based on the studies performed to date. Among the various views of human-robot interaction, the present work employs the dimensions shown in Table 1 to characterize a specific application of human-robot interaction.

The assistive robot to be used in this thesis research can be defined as a semi-autonomous mobile healthcare service robot with the aforementioned dimensions.

1.3.3 Evaluation of human-robot interaction (HRI)

Compared to traditional HCI, which has been established as a solid academic and industrial research field, human-robot interaction (HRI) is still a relatively novel topic

of study. Various research methodologies of HCI could be applied to the field of HRI with appropriate adaptations. Among research in human-computer interaction, heuristic evaluation [71] and cognitive walkthrough [100] are the most widely used methodologies to evaluate the usability of the system. Heuristic evaluation employs experts to investigate the system and find problems based on a list of easy-to-remember heuristics or principles. On the other hand, a cognitive walkthrough involves experts following a pre-defined order of procedures to evaluate the system and ensure that it has a logically sound structure for users to follow. Although heuristic evaluation was originally developed to be used for the evaluation of computer interfaces, especially in desktop computing environments, other variants of heuristics have been developed and applied for other purposes. A group of researchers at the Georgia Institute of Technology developed a set of heuristics to evaluate design guidelines and standards used by professionals to design products that are accessible to people with disabilities [13, 56]. In the field of HRI, a slight modification of the original HCI heuristics was suggested as shown in Table 2.

The suggested heuristics to be used to evaluate HRI are much in accordance with the Nielsen’s original heuristics, which is understandable because HRI and HCI are closely related. However, modification of the usability heuristics may be required for application to the evaluation of assistive robots because HRI has a lot of unique issues not found in HCI such as issues of physical interaction between moving manipulators and human body parts.

Although there is no evaluation methodology of HRI widely accepted as a norm, a few examples of evaluation studies of HRI issues have been published in recent years. Yanco, Drury, and colleagues [104] evaluated different implementations of HRI in a search and rescue mission contest (see Figure 2). The robots used in search and rescue missions usually perform in autonomous way, although the controllers (contest participants in this case) use a remote control device to monitor the robot

Table 2: Heuristics in HCI and HRI [103]

Nielsen’s Heuristics	Nielsen’s Heuristics Applied to HRI
Does the program speak the user’s language?	Is the robot’s information presented in a way that makes sense to human controllers?
Does the program minimize the user’s memory load?	Can the human(s) control the robot(s) without having to remember information presented in various parts of the interface?
Is the program consistent?	Is the interface consistent?
Does the program provide feedback?	Does the interface provide feedback
Does the program have aesthetic integrity (e.g., a simple design)?	Does the interface have a clear and simple design?
Does the program help prevent, and recover from, errors?	Does the interface help prevent, and recover, from, errors?
Does the program follow real-world conventions?	Does the interface follow real-world conventions, e.g., for how error messages are presented in other applications?
Is the program forgiving; does it allow for reversible actions?	Is the interface forgiving; does it allow for reversible actions?
Does the program make the repertoire of available actions salient?	Does the interface make it obvious what actions are available at any point?
Does the program provide shortcuts and accelerators?	Does the interface provide shortcuts and accelerators?

activities and give high-level commands. This study evaluated the HRI observed when the robots were controlled by both contestants and subject matter experts. In general, this evaluation study focused on the graphical user interface (GUI) of the controllers (see Figure 3), as the remote control was the essential part of HRI in this application. Therefore, the evaluation method of HRI reported in the study is somewhat similar to evaluations performed in traditional HCI studies, in which GUI issues are investigated (e.g., displays and input methods in mobile / portable devices, as well as desktop counterparts).

As robots are perceived by humans to have a more human-like existence rather than just a machine, an emotional and/or social relationship could be established

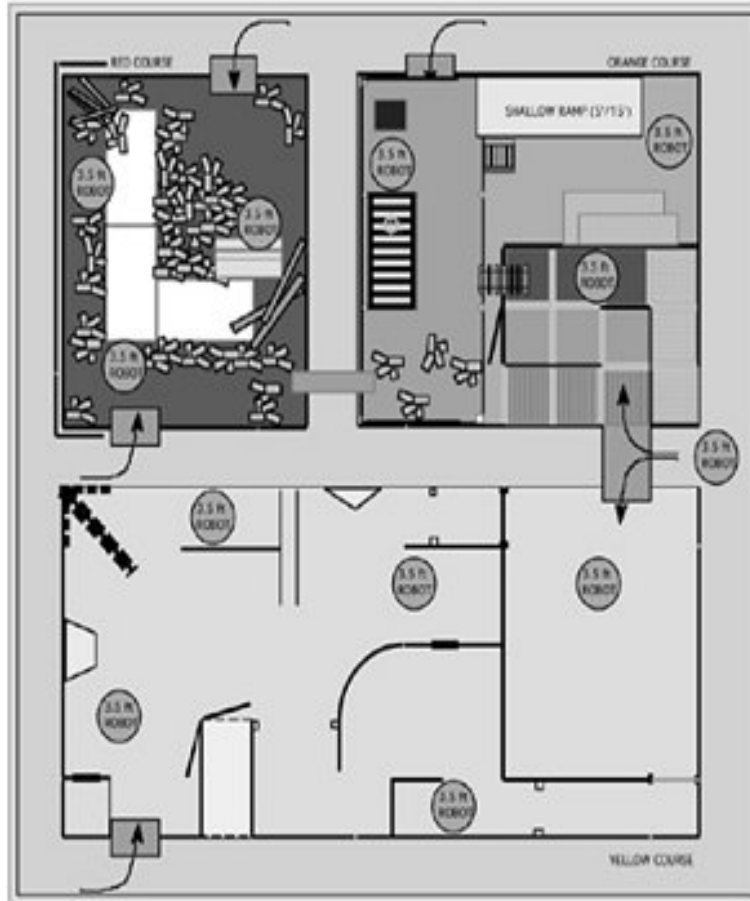


Figure 2: Test area of robotic competition [104]



Figure 3: Sample GUI of robotic competition [104]



Figure 4: A partner robot interacting with a child [43]

between the human operator and the robot. This anthropomorphic attitude was observed long before the development of intelligent robots. For example, an interactive computer agent named Eliza, developed in 1960s, was reported to establish human-like relationship with users [99]. Therefore, robots cannot only perform practical tasks, such as transportation, but can also serve as a partner to humans. Some researchers call this a “partner robot.” Kanda and colleagues [43] reported a field study in which Japanese elementary school students interacted with humanoid robots (see Figure 4). In the study, students were observed to establish a social relationship with the robot while the robot was helping them to learn English.

Huttenrauch and Eklundh reported a study involving the development of a service robot named CERO designed to help elderly people to transport light objects in office environments [38] (see Figure 5 and 6). They employed a task analysis method to inform the early stages of design, followed by long-term field testing with human users and the developed prototype. After a training period in which users tested the robot with help from engineers, the robot was inserted into the user’s home environment without direct observation, although log files were collected. The long-term user study



Figure 5: CERO service robot[38]

revealed problems with the robot usage, as well as actual usage patterns.

1.3.4 Robotics in healthcare

The use of robots in healthcare has expanded in several directions. Medical and surgery robots are designed to help physicians treat patients. Since the first clinically approved robotic camera holding system for laparoscopic surgery AESOP were developed to support robotic surgery, tele-operated surgical robots such as Da Vinci system [5] were commercialized to help surgeons to perform complex and delicate operations without directly contacting patients. These robotic technologies also advanced to enable tele-medicine, whereby doctors in remote locations could perform patient treatments including surgery.

Assistive robots are distinct from medical robots because they are designed to assist activities of daily life rather than helping diagnosis or treatment of diseases.



Figure 6: CERO unloaded by an elderly user [38]

Some researchers focused on assisting psychological, communicative, and social lives of people including elderly people having mental problems or children with developmental problems, such as autism. In 1990s, the AURORA project tried to develop an autonomous mobile robot to investigate the possible use of robots to mediate communication between people with autism and others [17]. Other researchers developed companion robots, such as PARO, a seal robot to assist elderly people [97] or autistic children [52].

The daily lives of people with motor impairments can be greatly enhanced with the application of robotic technology assisting physical tasks. The application of robotic technology in the field of assistive technology for people with motor impairments can be generally divided into two directions: mobility and manipulation. Mobility refers to the ability of movement from one place to another, which is largely dependent on the legs and feet of the human body. Even for people without motor impairments, various types of vehicles have been used for extending mobility. For those with motor impairments who have difficulty in walking, wheelchairs and powered



Figure 7: Semi-autonomous robotic wheelchair, TIN MAN II [64]

wheelchairs are the major devices used to improve mobility. Robotic technologies related to obstacle avoidance and route finding which were originally developed for the creation of autonomous machines were applied to create autonomous or smart wheelchairs. Although the function of autonomous mobility is a preferable feature, an entirely autonomous robotic wheelchair would be both hard to develop and impractical. With the involvement of human operators, use of a controller, such as a joystick, and providing limited autonomous functions, such as obstacle avoidance, would be a more practical approach. Development of low-cost robotic wheelchair with semi-autonomous features was reported in 1990s [64]. The second prototype resulting from this research is shown in Figure 1.3.4. It was developed as an add-on microprocessor unit and joystick controller to an off-the-shelf wheelchair.

The other application direction for robotic technologies lies in providing manipulation capabilities to develop assistive manipulation robots such as presented in this thesis. Manipulation refers to handling physical objects, mainly by the human hand without external aid. Therefore, impairments of the arm, hand, or fingers make manipulation tasks very difficult. Even when the upper limbs are intact, if the human has limited mobility, some manipulation tasks would still be very difficult. For example, people sitting in a wheelchair cannot pick up an object which was dropped on the floor because the intact arm often cannot reach the object. Manipulation of objects is one of the fundamental features of a robot. In fact, many of industrial assembly robots are just huge, powerful, and accurate manipulators. Many people with severe motor impairments spend much of their time in a wheelchair. Thus, the idea of attaching a robotic manipulator onto a wheelchair was a major research and development trend including the MANUS robot arm [53, 54]. Figure 8 shows an individual with spinal cord injury using a wheelchair-mounted robot arm to drink from a cup.

The MANUS arm can be controlled by a human user using a joystick or control pad. Although these controllers are relatively easy to use, it requires a substantial level of manual dexterity. Additionally, controlling a multi-degree-of-freedom device using a controller is a task which is relatively difficult to learn. The manipulator device has a broad range of applications, such as simple object fetching to assistive feeding to more complex jobs such as operation of other devices. Because manual tele-operation of robot arm is not feasible for some patients, such as those having spinal cord injury, some researchers utilized head movement [39] or electromyography (EMG) signal [109] to control meal assistance robots called “my spoon”. However, because tele-operation of manipulator controls requires a clear burden to operators with severe motor impairments, intelligent robot systems having autonomous functionality is ideal, if not necessary. Kawamura and colleagues developed an intelligent



Figure 8: A spinal cord injury patient using MANUS robot arm [54]

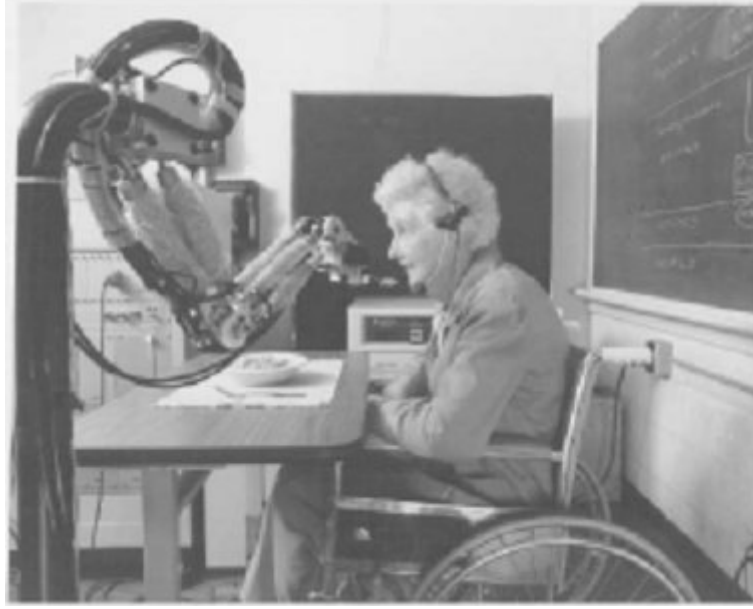


Figure 9: ISAC robot for feeding [46]

robotic system named ISAC to help feed individuals with physical disabilities [46] (see Figure 8).

Compared to the MANUS arm, the ISAC robot system does not require direct control by a human user but, rather, utilizes computational intelligence such as 3-D face tracking and object recognition to automatically perform the feeding task. These intelligent robotic systems can provide more convenience for individuals by reducing their mental and physical burden. However, the utility of the intelligent robots is likely dependent on pre-determined knowledge of the specific task and the environment in which the task occurs, even though advanced robots do possess learning capabilities. In addition to the technical challenges encountered during development, the implementation of this type of highly intelligent robot would be quite expensive.

The approach being taken in this thesis research is to develop a autonomous robot requiring limited control by the user. The user can give higher level commands to accomplish a specific task of object retrieval, such as through indicating the position of object rather than directly controlling (i.e., directing) the robotic device. The



Figure 10: Handy1 prototype [88]

goal is to develop a mobile robot which can move independently from the position of the user, independent of his or her wheelchair. Compared to the wheelchair-attached manipulator approach, a mobile manipulator has more flexibility to reach objects and will work even when the user is not in a wheelchair.

1.3.5 Assistive Robotic Manipulation

Over the decades, researchers have studied manipulation assistance for individuals with impairments and the elderly. The first group of applications focused on robotic assistance by developing workstations that were designed to help users to tasks performed at offices and factories [15, 91, 92]. Handy 1 is a workstation type robot useful for eating and drinking assistance [88] (see Figure 10). Although these workstations were useful in situations where tasks were in relatively known, controlled patterns, assisting manipulation in naturally occurring, wider variety of applications required additional mobility than the typical robotic arm possesses. Mounting a robotic arm to a wheelchair was an initial approach to achieve mobile manipulation. Exact Dynamics successfully commercialized a manipulator arm called MANUS [55], which could be used in either a wheelchair-mounted [61] or mobile robot application [14]. An independent mobile platform provides added mobility because the user need not be in

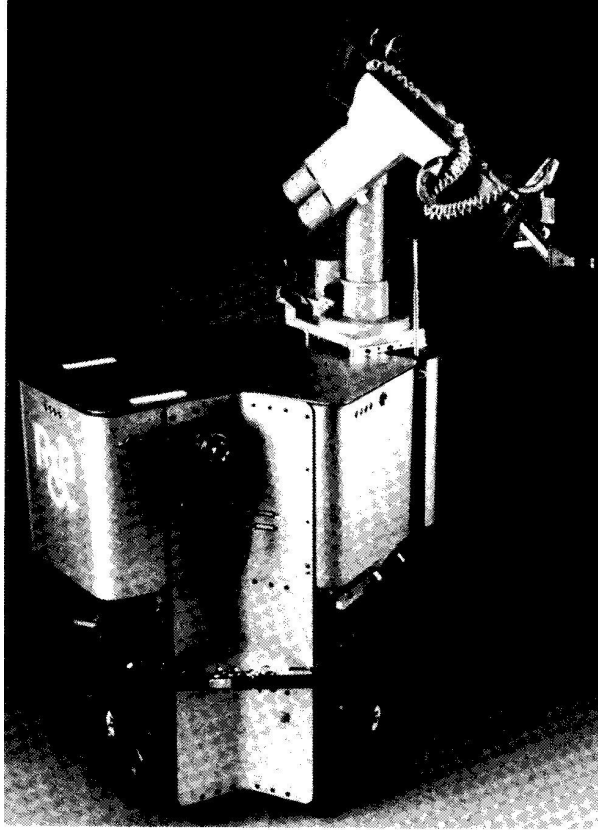


Figure 11: MoVAR robot base with instrumented bumpers and joystick [91]

close proximity and the wheelchair need not have a larger footprint. One of the earliest mobile assistive robot study is the MoVAR project where VA/Stanford researchers used a PUMA 250 arm mounted on a three-wheeled omni-directional mobile base [91] (see Figure 11). As a joint research project between European nations, the MOVAID project implemented a prototype system combining fixed workstations and mobile manipulation robots for disabled and elderly people [16]. Mobile assistive robots are capable of a fetch and carry task which can serve as the basis of a wider range of domestic tasks [8, 31]. Earlier manipulation assistance relied on human control by either joystick or keypad input or speech input. However, the limited capabilities of target user populations require investigation into increasing autonomous control for manipulation tasks. Recently researchers utilized images from manipulator-mounted stereo cameras to implement semi-autonomous object grasping [61, 74, 89]. For example,

Remazeilles and colleagues [74] installed various sensors on the gripper of MANUS arm to enhance the grasping capabilities of this robot (see Figure 12).

1.3.6 Object fetching and delivery

Activities of daily life (ADL) [57] have been used to evaluate the decreasing physical capabilities of individuals with respect to everyday activities such as eating, bathing, dressing, toileting, and transferring between places. Many national scale surveys have been conducted to understand the patterns of problems in ADL experienced by large population for a long time period [101], and a more recent longitudinal study of national survey data shows certain patterns of occurrences of deficiencies in ADL [21]. Disabilities leading to deficiencies in ADL considerably decrease the independence of these individuals. Object retrieval is one of the most basic ADL tasks, which is actually composed of different, individual activities. If a person cannot effectively grasp an object and hold it or move it, most ADLs would pose difficulty for this individual. Thus, the lack of object retrieval capability often results in lost independence because an individual who cannot effectively perform this task would need external help from either another person or some other form of assistance for many related tasks. Beside human help, several approaches utilizing animals such as monkeys [33], and dogs [27] exist but they also have issues of costs and reliability.

Some robotic researchers have studied object delivery between robots and humans. Shibata and colleagues [79] studied the motions involved when two humans hand each other an object to determine the trajectories and velocities of their hands during the task. Kajikawa and colleagues [42] have also used these human hand trajectories to simulate a human delivering an object to a robot using potential fields. Agah and Tanie [2] investigated human interaction when a mobile manipulator handed over an object to a human and designed contention architecture through a simulation study. Recently Jindai and colleagues [41] used a 2D planar robot to assess human

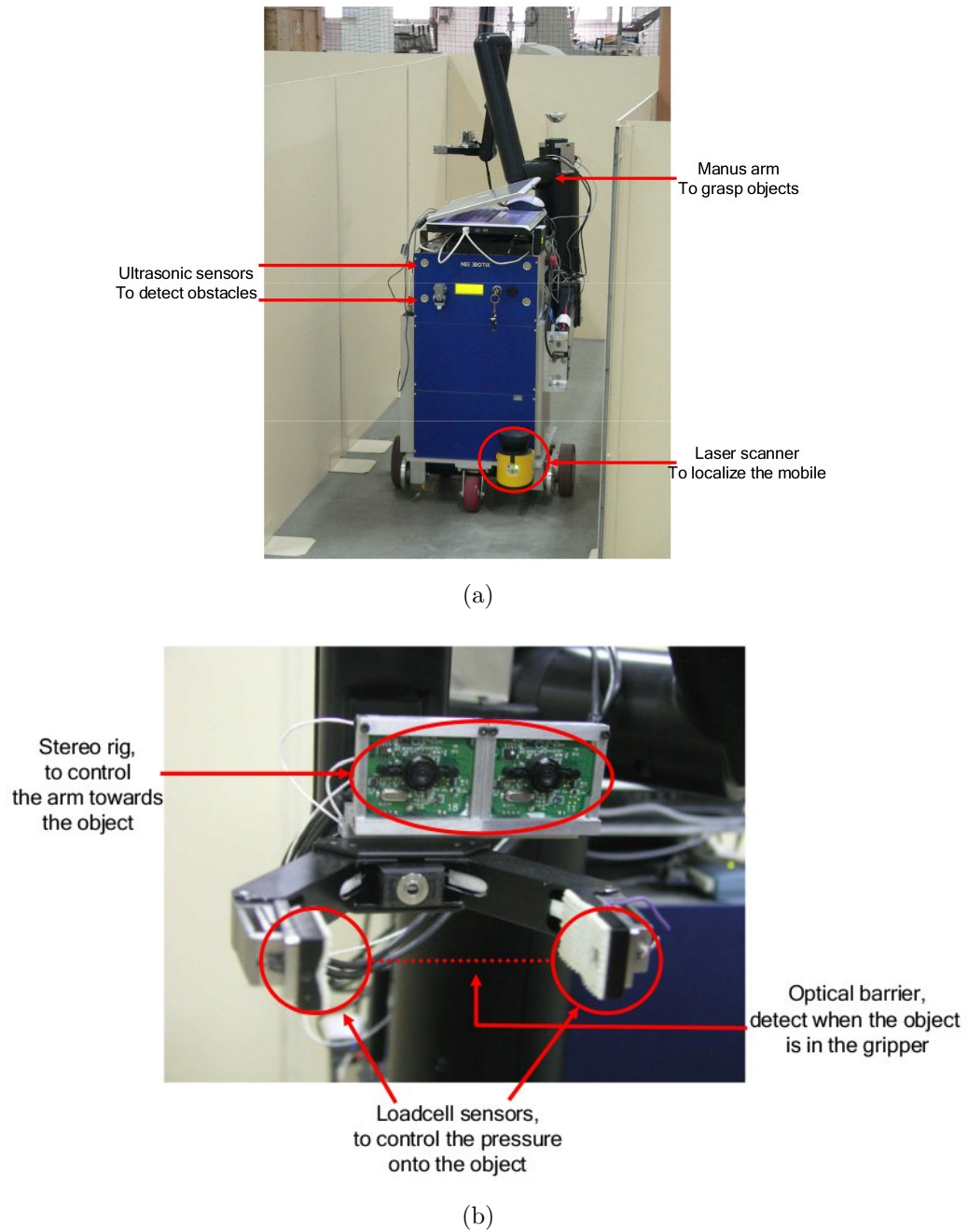


Figure 12: (a) MANUS arm on a mobile platform (b) Sensors added to the gripper [74]

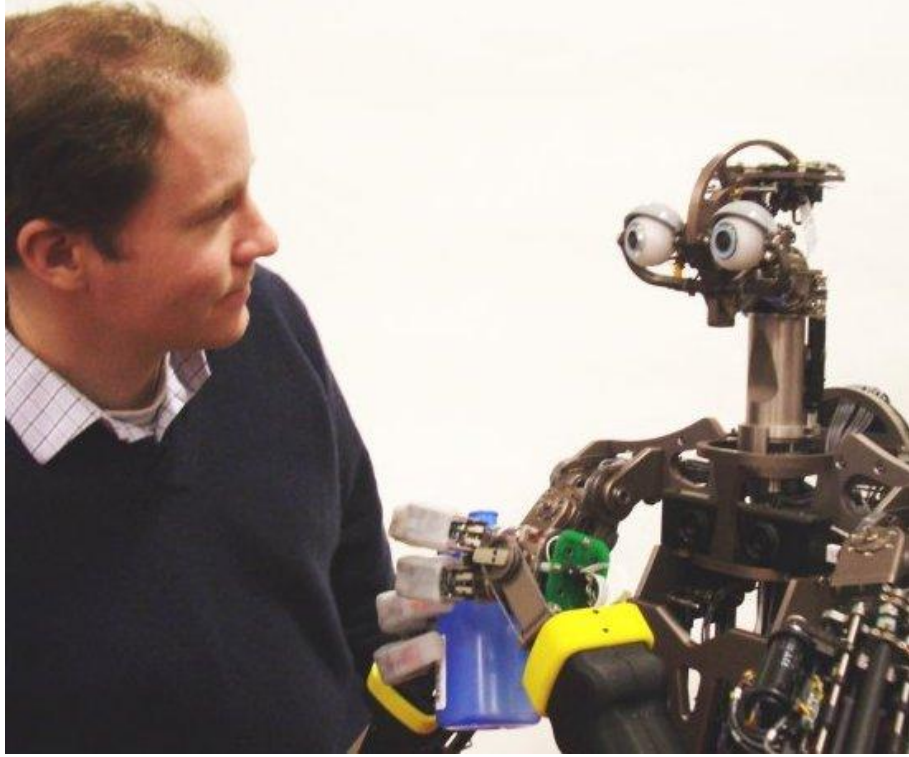
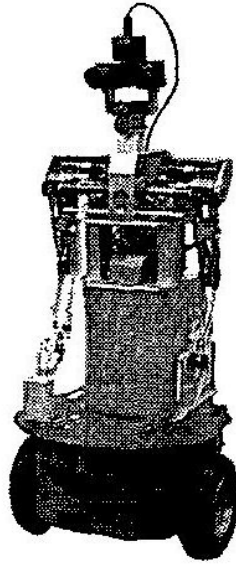


Figure 13: Humanoid robot, Domo

preference for delivery velocities and positions during a human-robot object hand-over. Edsiger and Kemp [22] used passive compliance and force sensing actuators to implement direct handing of objects between a humanoid robot Domo (see Figure 13) and a human user. Hori and colleagues [36] studied the object delivery task by the H3 humanoid robot in a sensorized environment (see Figure 14). They distributed ultrasonic sensors to the walls and ceiling to enable the robot determine the 3D positions of humans and other objects in order to perform delivery tasks.

More recently, with the prospect of service robots interacting with humans in the future, Walters and colleagues [98] focused on the psychological effects of robot behaviors on the users. They conducted user studies with different approach methods (see 15) in delivering objects with a commercially available PeopleBot, a mechanical-looking robot with no intention to make it look or behave exactly like a human. Their results showed that most subjects disliked a frontal approach when seated and prefer



(a)

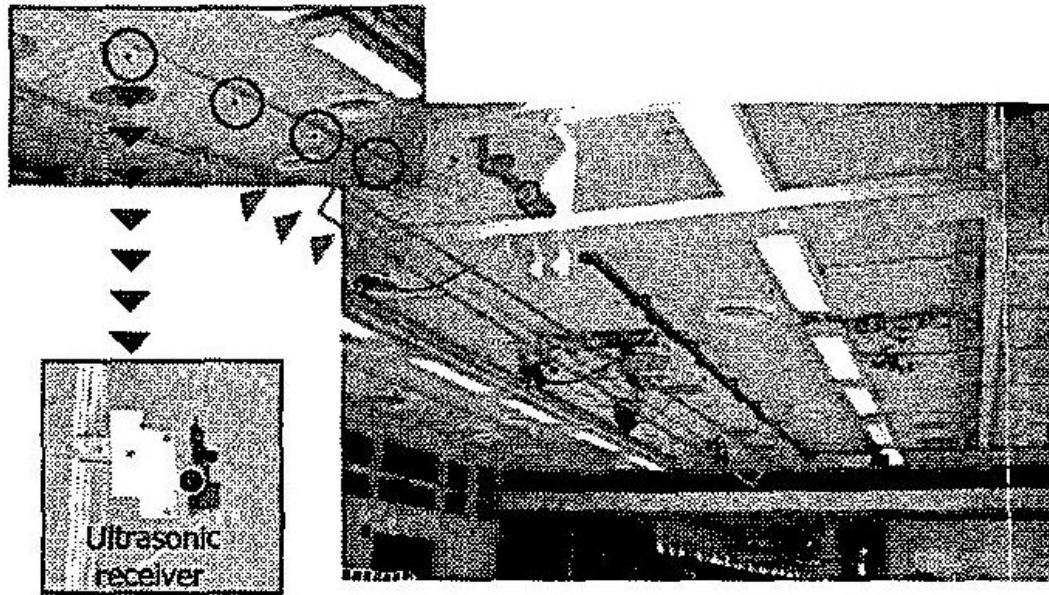


Figure 14: (a) H3 robot (b) Sensorized environment [36]

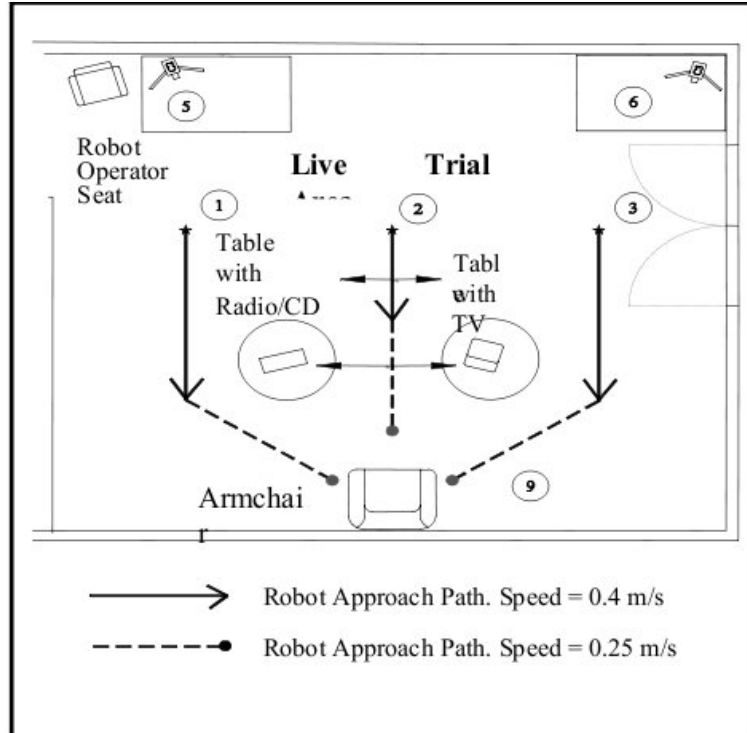


Figure 15: Live trial area [98]

either the left or the right hand side approach directions. Some stated that they felt that the robot was “slightly threatening” and “seemed too aggressive” and were “concerned about the robot running into me.” In general, humans do not like to be approached from behind by a robot, preferring the robot to be in view even if it has to take a non-optimal path. They also found that humans prefer approach distances for robots comparable to those found in studies examining common human-human social distances.

1.3.7 Motor impairment and ALS

1.3.7.1 Human capabilities and impairments

Generally speaking, people tend to divide themselves into normal and handicapped categories, with the normal group possessing the common sensory, cognitive, and motor capabilities, while the handicapped group possess a disability or limitation in their capabilities to perform common mental and physical daily activities. However,

Table 3: Human capabilities and impairments

Categories	Sub-categories	Capabilities	Related impairments
Physical	Sensory	Vision	Blind, limited sight, color-blind
		Hearing	Deaf, limited hearing
	Physical	Dexterity	Injury, neurological diseases (Parkinson’s disease, ALS)
		Standing/walking	
Mental		Decision making, learning, memory, consciousness	Dementia, Alzheimer’s disease

the concept of being “normal” is a relative concept, as there is an infinitely varying degree of mental and physical capabilities. Although classification of human impairments is quite complex, I would like to divide them into: 1) mental impairments; and 2) physical impairments. Various human capabilities and related impairments can be categorized as shown in Table 3. Mental impairment is often more subtle and difficult to diagnose while physical impairments are relatively easily diagnosed and treated.

The physical functioning of human bodies can be divided into input from outside (sensing) and output from the body (motor). Sensory functions gather data from outside of the body and process the data with perceptual processes into information to be transferred through the nervous system [78]. Humans have visual, auditory, olfactory, gustatory, tactile, and other miscellaneous senses. The sensory functions may be limited or totally absent for various reasons, resulting in sensory impairments, such as visual impairments (blindness, low vision, color blindness) and auditory impairments (deafness, hearing difficulty).

1.3.7.2 *Motor impairments*

Motor functions work in the opposite direction compared to sensory functions. As in other animals, humans can move their body with muscles, tendons, and ligaments. A human musculo-skeletal system is a complex biological system which collaborates with the nervous system, as well as sensory organs. To function appropriately, the

balance and inter-relationship between whole body parts are essential. Among the complex system of motor functions, free movement of the four limbs (i.e., arms and legs) is of particular importance for human life. Sometimes the term of physical disability is used in place of motor impairments. Physical disability can be defined as “conditions that substantially limit one or more basic physical activities such as walking, climbing stairs, reaching, lifting, or carrying” [90]. However, because sensory impairments also cause “physical disability”, motor impairment is supposed to be a more appropriate term and will be used in this work.

Motor functions can be damaged by injuries and diseases. Spinal cord injury is a common cause of motor impairments, which can sometimes affect the whole body due to the harm to the central nervous system. Amputation of one or more limbs also significantly decreases motor capabilities. Other than these severe cases, people can injure their bodies during daily life, such as working at home or in offices, playing sports, and so on, sometimes resulting in temporary motor impairments.

Because motor capabilities depend on the flow of information to and from the nervous system, diseases affecting the nerve system can also limit the motor capabilities. Infectious diseases, such as polio, can cause paralysis of the spinal cord and devastate normal motor functions. Many of those infectious diseases can be prevented through vaccination or otherwise treated with medical advances. However, amyotrophic lateral sclerosis (ALS) is a disease for which there is no known cause or cure yet. ALS is one of the most common neurological diseases resulting in motor impairment. At any given moment, it is estimated that there are around 30,000 Americans diagnosed with ALS [86]. ALS debilitates the function of motor neurons, which eventually affects all voluntary muscle movement of the entire human body. ALS is a very severe, progressive disease, which starts with minor symptoms, such as muscle stiffness, and progresses to the loss of muscle movement across the entire body, eventually leading to death.

Although ALS is a deadly disease affecting the entire body, it is reported that the cognitive and mental abilities of the people with ALS remain relatively unaffected. In addition, a study with ALS patients reported that many of the patients often have a positive attitude regarding their condition and their life despite their tragic physical condition [108]. Some patients interviewed in the study indicated that they think more of their family and social relationships even though contact with their loved ones is often decreased. The loss of contact with their family and friends is largely due to the loss of independence in their daily life. Therefore, assistance via technologies, such as robotics, would also be beneficial for these individuals to maintain their social relationships and to help increase their quality of life during their remaining survival time.

To aid individuals with physical impairments, it is essential to ask the people possessing those impairments, which tasks in their daily life are most difficult for them to perform. Additionally, it is equally necessary to discover what needs may be able to be met with technological solutions and what expectations, anxiety, and so on these individuals may have regarding the use of assistive robots or other technology. Stanger and colleagues [82], examined the survey results reported from six different studies related to the development of devices for assisting manipulation, including the MANUS manipulator. The investigated studies reported the results of pre- and post-development surveys of users regarding which tasks are high priority with respect to their needs and expectations. Simple object fetching and retrieval was among the most frequently-cited tasks with which participants expected to receive help. Other tasks such as personal hygiene, food and drink, and entertainment, were also indicated as tasks requiring assistance.

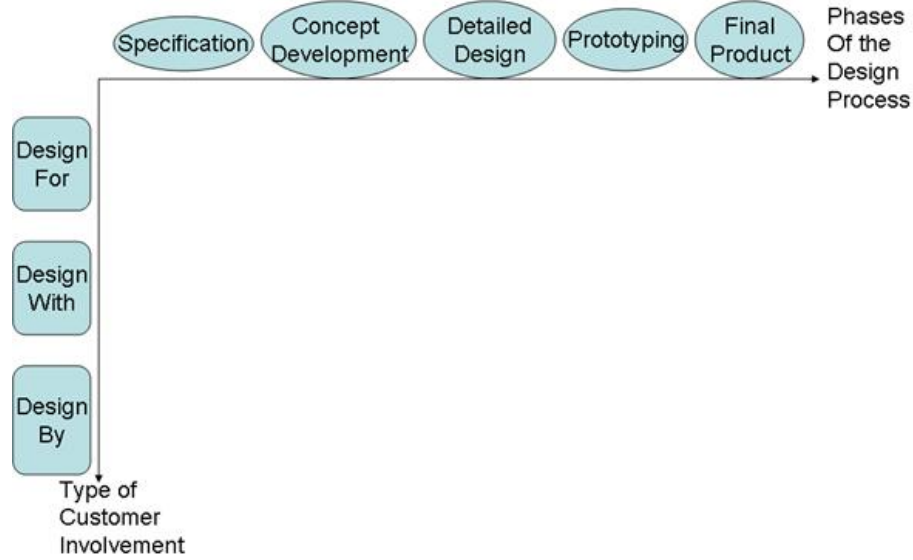


Figure 16: A framework of customer involvement [45]

1.3.8 Involving users in product / technology development

Since the modern industrial market shifted from producer-oriented to consumer-oriented products and services, the importance of finding and meeting the needs of general consumers and specific groups of target customers has grown. Kaulio [45] reviewed various methods of user involvement in product design and suggested a two dimensional framework in product development phases and type of user involvement. This framework is illustrated in Figure 16. In practices of user involvement in product life cycle, feedback of users helps design changes and these changes will receive user feedback. This feedback loop results in the iterative design process.

In the field of usability in human-computer interaction, user centered design (UCD) is an established term that refers to various activities involving users in design process. Researchers applied UCD in various application domains including user interface design [32], website design [19], and human-robot interaction [1]. Based on literature review and surveys of participants in a human computer interaction conference, Vredenburg and his colleagues [96] surveyed the existing UCD methods

and the rankings in terms of importance and frequency of use. The survey results showed that participator design, card sorting, informal expert review, surveys, prototype without user testing, user interviews, and formal heuristic evaluation ranked higher in importance and frequency compared to other study methods. The present research used the method of interview and survey in the user needs assessment while human evaluation studies employed user testing.

CHAPTER II

THE ROBOT SYSTEM CONFIGURATION

2.1 Human and machine components

The assistive robot used in this thesis work consists of a robot hardware and software system including a mobile base, manipulator, on-board computers, and various other sensors and software systems. However, the whole picture of the assistive robot system should also include a human operator or user. The assistive robot system for this proposed research consists of one robot and one human user. As the overarching goal of the robot is to assist the human user, the major human component of the system can be called an “assisted user”. In this case, this individual will possess motor impairments necessitating the use of an assistive technology or system. Understanding the capabilities and preferences of the assisted users will be of utmost importance for the successful development of the robot system.

Besides the assisted user of the system, the system includes other human components that may indirectly interact with the robot. In many cases, people with ALS receive help from their caregivers (mostly spouses or other family members). The caregivers, or the “assistant user”, generally possess a higher level of motor capability than the assisted user and do not have a need for robot assistance. However, assistant users may have to interact with the robot to help the assisted user. For example, when the robot needs maintenance or a change of configuration, the assistant user may have to use the robot’s advanced functionalities such as safety, setup, or maintenance. Therefore, the user interaction of the assistant user may not be the same as the assisted user.

The machine part of the robot system consists of robot hardware and software

components as introduced in the following sections. It should be noted that although the overall structure and implementation of the hardware and software have been consistent through this thesis research, the robot evolved considerably during the course of the user studies. Therefore, this chapter introduces the general configuration of the robot hardware and software. In the two evaluation studies in later chapters, any specific hardware and software modification and improvement made to the robot are discussed separately. The details of any changes made are described in Implementation sections of these chapters.

2.2 Robot hardware components

As described in Figure 17, the physical robot looks like a tall vacuum machine. On top, the head unit contains a camera system for observing the surrounding environment. The vertical lift or linear actuator, called Zenither, is used for vertical movement of the arm, including a 6 DOF (degree of freedom) manipulator. These components are placed on a vehicle-like structure, called a mobile base.

2.2.1 The robot head

The head of the robot performs as an eye or visual system for the robot, containing two different types of camera systems. The elliptical mirror in the center of Figure 18 constitutes a catadioptric system (0-360 Panoramic Optic) with a lens on the bottom of it. With the help of the shape of the mirror, the lens can get a comprehensive scene of large areas. The scene includes an area that is horizontally 360 degrees (except for a small area blocked by the robot Zenither) and vertically from the floor to the ceiling. This catadioptric system enables monitoring of the whole room with an overview image. Although the catadioptric camera is useful to get on overview, the resolution power of the camera is limited. Therefore, a stereo camera system, mounted on a pan and tilt unit, is used to get detailed images from the scene. When the robot finds an area of interest, such as a laser pointer light, in the overview picture, it computes the

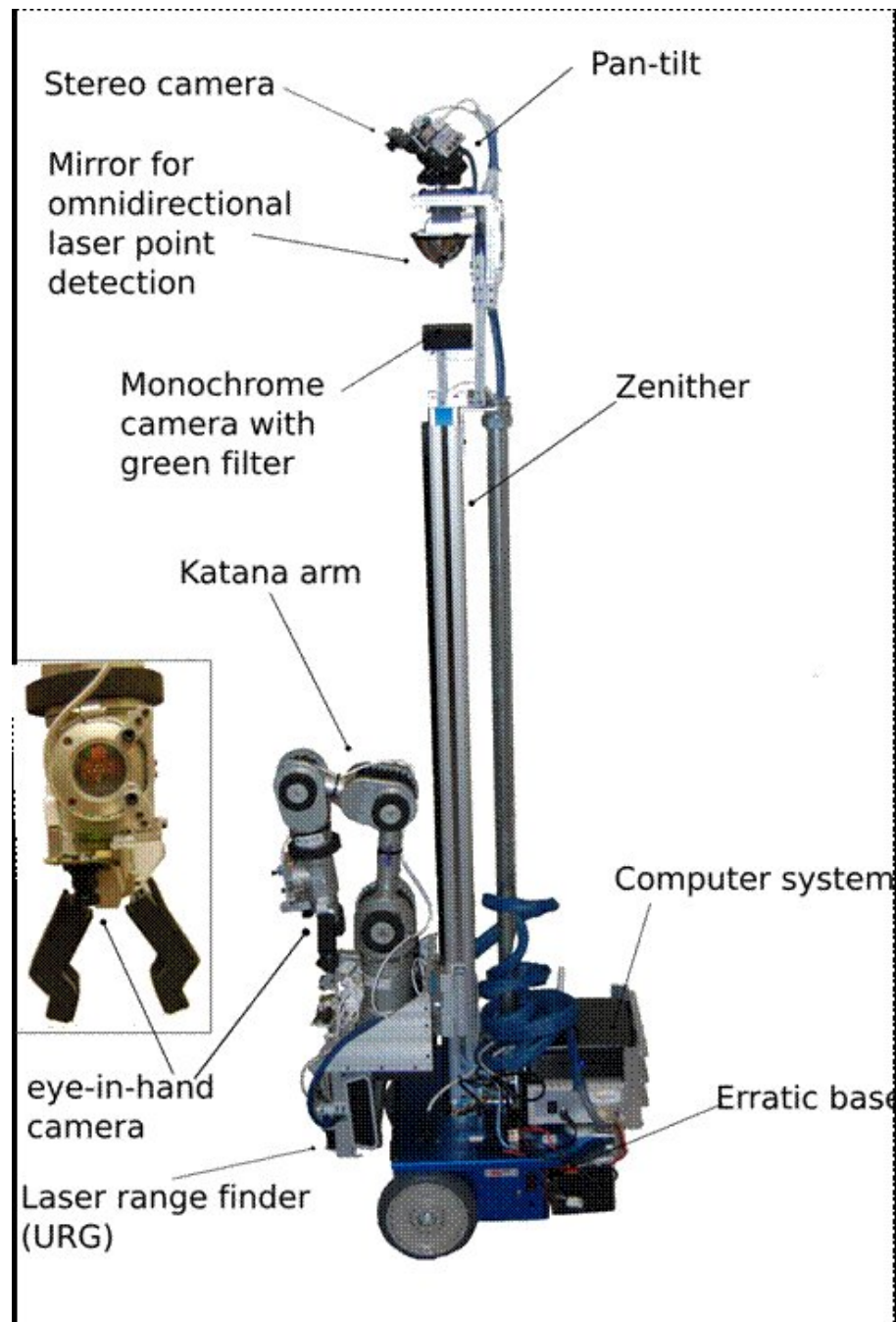


Figure 17: The robot with parts description



Figure 18: The robot head

position of the area and moves the stereo camera in two dimensions, that is to say, pan and tilt. With the smaller viewing area and increased resolution, the stereo camera can obtain a higher fidelity image on a detailed area which facilitates the computation of obtaining more accurate 3-dimensional positioning of the target object.

2.2.2 The arm

A Katana 6 DOF manipulator developed by Neuronics AG is employed for the manipulation functionality (see Figure 19). The six-degrees-of-freedom of the manipulator enables the arm to move itself to position the end effector, or gripper, into any 3D position within reach. To increase the reach of the manipulator on the vertical scale, it is mounted on the vertical lift (i.e., the Zenither). Currently, the gripper of the



Figure 19: Katana robot used in the robot arm [68]

Table 4: Specification of the manipulator

Parameter	Value
Precision	+/- 0.1 mm
Operation radius	60 cm
Weight	4.3 kg
Payload	500 g
Velocity	90° per sec. (concurrent motion of all axes possible)

robot consists of a simple two finger apparatus, which is effective for grabbing most objects but may have some difficulty with flat objects. Alternative designs for grippers to overcome this shortcoming are under development. Table 4 shows a summary of the specifications of the manipulator.



Figure 20: Videre Erratic mobile base [94]

2.2.3 The mobile base

The mobile base is a vehicle platform for transporting the whole robotic system. It is built with a commercially-available mobile platform named Erratic from Videre Design [94] (see Figure 2.2.4). It holds other hardware components of the robot and is controlled by an on-board computer with an Ethernet link. It is equipped with a URG laser finder with a 4 meter range and can move with maximum speed of 2.0 meter/seconds.

2.2.4 Robot software components

The software components of the system consists of the software equipped inside of the robot hardware and the software residing inside an external personal computer (PC) which sends commands to the robot as scripts. The communication between the external PC and the on-board computer is established with a wireless Ethernet connection. The control software in the external PC is written in the Python programming language to facilitate a faster development timeframe. The external PC is configured based upon the Linux operating system (Ubuntu).

2.2.5 Point and click interface

The core feature of the user interface of the robotic system is called the “point and click interface” with analogy to the point-and-click interaction style used in common graphical user interfaces (GUIs). This interface enables the user to point an object in the 3 dimensional world with a conventional laser pointer, similar to the use of a mouse pointer on the 2 dimensional screen of a PC interface.

When a user turns on the laser pointer and orients it toward a specific object, the laser light emitted from the laser pointer is reflected on the surface of the object. When the user points to an object and stops movement of the laser pointer for a specific dwell time, it is recognized as a “click” command. The cameras on the robot receive the images of the scene and analyze it with vision processing algorithms. Because the reflected image of the laser light has a specific frequency and the shape of a small dot, the robot can distinguish the laser light from other images. To disambiguate the image and increase the sensitivity, a color filter is utilized to filter the light within the specific frequency range in order to amplify the color of the laser pointer. This object detection process is followed by object segmentation of the target object (e.g., an item that has been dropped or is otherwise unreachable) having the laser light.

Before the human evaluation, lab-based experiments were conducted to validate the performance of the developed interface [49]. The experiment used 10 different objects as shown in Figure 14. The experiment was conducted in four phases; 1) detection using the catadioptric camera, 2) locating with the stereo camera on the pan & tilt unit, 3) object segmentation, and 4) grasping the objects as depicted in Figure 21. The experimental results showed that 100% successful omni-directional detection and 100% successful pan & tilt of stereo camera. 94% of trials were successful to the complete object detection with object segmentation. For grasping objects, the initial experiment was successful to grasp 9 out of 10 objects with the only exception being a thin, flat cordless phone (see Figure 22). With some follow-up modification of the

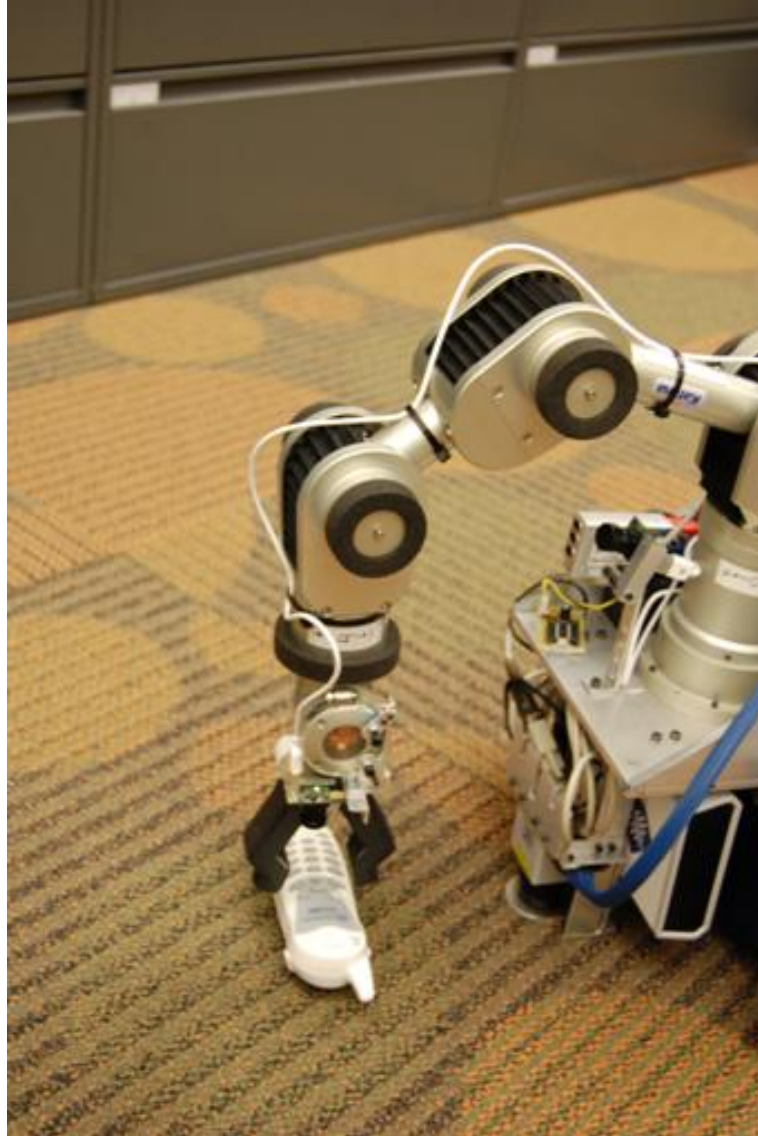


Figure 21: The robot grasping a cordless phone

system, the robot did manage to successfully grasp the cordless phone.

2.3 Alternative interfaces

2.3.1 Modified laser pointer interface

For people with limited manual dexterity, including several ALS patients, the laser pointer device still presents a, sometimes significant, physical burden due to limited shoulder, arm, elbow, wrist, or hand movement. While some of the patients experience difficulty with gross arm movement, they still retain sufficient motor ability in their



Figure 22: Objects used in the lab experiment

hands. One alternative I considered is to develop a remote controlled laser pointer, by which the users can retain the use of a joystick controller on their power wheelchair. As many of the ALS patients are familiar with this joystick control, the control interface paradigm has been suggested as a natural, mediating controller to move the laser pointer. A laser pointer can be mounted on a pan and tilt unit which is fixed on a wheelchair. The low-cost pan and tilt unit with joystick input controller shown in Figure 23, can be used to create this mediated laser pointer interface. Because the joystick control has two degree of freedom; pan and tilt, it is significantly easier to control compared to control of 6 degree of freedom manipulator itself. The remote control unit can be developed and operated, while decoupled from the robotic system. In this thesis research, I did not implemented this control system but devised another alternative of head-mounted laser pointer.

After considering development of mediated laser pointer interface, I found that head-mounted laser pointer would be beneficial to users with limited upper limb dexterity but with capabilities of moving the head. In the needs assessment, we observed



Figure 23: Pan & tilt device with joystick control

that all the participants could move their head with relative ease even when their mobility was limited in upper and lowerlimb. Therefore, I designed and developed a ear-mounted laser pointer as an alternative laser pointer interface rather than developing remote controlled laser pointer. The laser pointer control used in the studies presented in this thesis work consist of a common, handheld laser pointer and a modified, ear-mounted laser pointer, as will be discussed in more detail.

2.3.2 Handheld user interface

In addition to the laser pointer-based control interfaces described, an alternate user control interface was also developed for evaluation. If the laser pointer interface can be called a 3D point and click interface, this alternate interface design uses a more traditional 2D point and click interaction paradigm. Although the 3D point and click interface is expected to provide an intuitive and convenient interface for people who can use it, there are cases where this interface is not appropriate or will prove to be cumbersome, unusable, or ineffective. Those individuals with severe motor impairments may have great difficulty in moving their arms and hands. For those individuals, the laser pointer or mediated laser pointer interfaces would not be practical. However, many of these individuals still have access to computers through the use of assistive interface technologies, such as voice command or eye-gaze interfaces. Another case where the 3D point and click control paradigm falters is when the object

is out of sight of the user. The 3D point and click interface assumes that the user and the robot share the sight of the potential target objects. If the object is blocked by other objects or is located in different room, a 2D point and click would be alternative interface. The 2D interface was be implemented using a handheld computer with a flat screen display with a touch screen and is described in 5.

CHAPTER III

USER NEEDS ASSESSMENT

Identifying the wants and needs of prospective users is essential to the development of any product or technology. As the target user population of the assistive robot is ALS patients, and the designers and developers of the robot do not have an adequate familiarity of living with these types of disabilities, interviews with users and observation of their living environment are be crucial for development of a successful assistive robot system. I conducted the user needs assessment in following steps.

1. Recruitment of participants:

I recruited eight participants were recruited from the ALS patients who visited the Emory ALS center for clinics. I asked those patients interested in participation to sign a consent form and complete the demographic survey. After an introduction to the study was given and a digital camera and take home survey were distributed to each participant.

2. Photographing of objects in participants' environments:

I asked participants to bring home the digital camera home and take pictures of the dropped and unreachable objects in their environments and document the conditions in which the objects were dropped or became unreachable.

3. Interviews with participants:

Following a period of seven to ten days from the start of participation and home documentation (as described above), the research team visited the participants' places of residence. The interview included open-ended questions relating to how the participants interact with common, important objects on a daily basis.



Figure 24: Steps for User Needs Assessment

The user needs assessment strictly followed the procedures of human subject study in Georgia Tech and Emory University. The experimental protocol was created and submitted to both universities in December 2007 and were approved in February and January 2008, respectively. The recruitment and interviews were conducted in February and March 2008.

3.1 Introduction

For the purposes of this thesis research and related research projects, we developed an assistive robot named EL-E, pronounced as "Ellie". This robot is capable of object manipulation activities, such as locating, grasping, transporting, and handing objects and has been primarily designed to help individuals with severe motor impairments, such as those suffering from amyotrophic lateral sclerosis (ALS). Because the target user population of the assistive robot suffers from severe motor impairments, it is necessary for the designers and developers of the robot to acquire familiarity with the needs and everyday living conditions of these individuals. We believe the study of

user needs throughout the design and development process is essential in improving the usability and accessibility of the robot for the target user population. Interviews with users and observation of their living environments are crucial for success.

Thus, we conducted a user needs assessment with the following steps: 1) participant recruitment and initial surveys, 2) photographing and notepad-writing on occurrences of difficulty with object manipulation, and 3) follow-up interviews examining users' experiences with object manipulation problems and their expectations of the assistive robotic technology.

The photographing by patients and in-depth follow up interviews revealed several important insights regarding the needs and wants of participants with respect to robotic assistance with object retrieval. Various household objects of varying sizes, from a small medicine pill to an adult walking cane, commonly need to be retrieved and items such as telephones and walking canes are among the most important objects to be retrieved. It should be noted that walking canes were rated low in perceived importance for robotic retrieval in the following study of the ranked list of everyday objects. Although some patients think walking canes were very important, other patients, who do not use it, can perceive its importance very low. Individuals indicated that they dropped objects an average of 5.5 times a day during the observation period. It took an average of 9.4 minutes to retrieve the dropped objects but the retrieval time varied widely, with standard deviation of 25.4 minutes, depending on the nature and severity of the patients limitations. One patient had to wait 2 hours for the care giver to come.

All participants agreed on the potential value of an assistive robot capable of object retrieval and generally felt that the mobility and portability of the robot are important facets of its design. We asked participants to try to use a hand-held laser pointer as a controlling interface. Six out of eight participants could effectively aim the pointer to an object, but only three individuals indicated a high level of comfort

during use.

The results of the study provided valuable input for improving the design of the robot and are also expected to be useful for future robot development efforts aimed at object manipulation assistance. To help ALS patients retrieve dropped objects, and based on input received during this end user study, our lab developed a novel end effector technology for retrieving small objects from the floor and an ear-mounted laser pointer as a controlling interface, which decreases the upper-limb mobility needed to control the robot.

3.2 *Related works*

3.2.1 Assistive robotics

Academic research and commercialization efforts to apply robotic technology to help individuals with motor impairments have focused on improving one’s mobility and manipulation capabilities. Improving mobility of individuals with motor impairment was essentially achieved with the introduction of powered wheelchairs. Object manipulation is another obstacle for those with motor impairments. Those with limited arm and hand strength and dexterity have difficulty with lifting, carrying, and controlling everyday objects. People with lower limb disabilities also have problems with object manipulation because they cannot reach some objects, such as those dropped on the floor. As many people with motor impairment use wheelchairs, wheelchair-mounted manipulator arms have been developed and commercialized [53, 54]. However, wheelchair-mounted robots have limitations in flexibility of use, such as reaching objects located physically close to the human user or beyond the physical reach of the arm. Additionally, because direct control of a robotic manipulator requires significant efforts with regard to learning and upper limb mobility, a number of studies have focused on the development of technologies for autonomous manipulation [8, 30, 31, 47, 50].

As a result, we developed an assistive robot with autonomous manipulation capabilities, designed to meet the specific needs of object manipulation for individuals with severe motor impairment, such as ALS patients. The robot has a five degree of freedom robotic manipulator mounted on a vertical linear actuator. The robot can monitor an indoor space using an omni-directional camera and also view a specified area with higher resolution using a stereo camera. We built the robot system on a statically stable wheeled mobile base to navigate flat surfaces. One contribution of this robotic system is the user interface, which utilizes a common, inexpensive laser pointer. The robot detects the laser point on the surface of an object with its cameras and determines the relative 3D location of the identified object. This interface is analogous to the point-and-click interface used in personal computer 2D graphical user interfaces.

The 3D point and click interface using a standard, off-the shelf laser pointer is expected to reduce the mental and physical burden of users when controlling the robot compared to direct control of traditional manipulation arms. The robot has been previously tested in a laboratory setting, with very successful and promising results [69].

However, the design and testing of the robot was performed by researchers who did not suffer from motor impairments. Thus, understanding the needs of actual users with motor impairments has been recognized as crucial to the successful development of truly assistive robotic technology. The needs assessment presented in this study ultimately became the basis for conducting user studies with ALS patients as described in the next chapter.

3.2.2 User involvement in technology development

User-centered design (UCD) is an established field within the overall discipline of human-computer interaction, which refers to the various methods and activities used

to involve end users in the interface design process. In the field of rehabilitation robotics and orthosis, researchers conducted a number of surveys to understand the needs of potential users [82, 73, 34]. Many of the surveys focused on discovering which tasks of daily living should be prioritized in the development of assistive manipulation technologies. This was achieved by asking people with motor impairments and the clinical personnel who cared for them. Object fetching is one of the tasks that these studies identified as high priority. However, further investigation is needed to better understand the specific needs relating to the object retrieval task. In this study, we met people with motor impairments and observed their natural environments to gather information regarding the objects, environments, and expectations of the people regarding the mobile autonomous manipulation robot.

3.3 Preliminary patient contact

The official needs assessment and human evaluation required approvals from the internal review boards (IRBs) of the oversight institutions, the Georgia Institute of Technology and Emory University. Meeting both universities' requirement took longer than expected and the submitted protocols were finally approved on January and February of 2008 for Emory University and Georgia Institute of Technology, respectively. Informal meetings with patients were attempted before the IRB process to familiarize the experimenter with the clinic and the patients. At this time, informal dialog was conducted regarding their general acceptance and expectations of robotic technology for object retrieval tasks. The following contains the summary of these informal interviews:

- The first patient was an elderly, Caucasian male (over 70 years old), lacking motor movement of his arms. He was not officially diagnosed with ALS yet, although his physician feels that it is probable in the near future. With respect

to dropping objects, he mentioned that he frequently dropped pills and medication. However, he still possesses the ability to walk and bend to grab objects. He does not need an assistive object retrieval robot yet. From this dialog, we learned that some ALS patients in early disease stages do not have extensive needs for robotic technologies.

- The second patient is relatively young (about 30 years old), Caucasian male. He uses a power wheelchair and while lacking the ability to walk, can freely move his arms and hands. However, he has limited manual dexterity. When he heard of the possible use of a laser pointer interface, he said that a button-based interface was bad for him because his fingers did not move easily or accurately. He suggested that using pressure to click the laser pointer through squeezing with the entire hand (e.g., fingers and palm), rather than by a single finger alone, would be a more appropriate interface. He indicated that he frequently drops objects such as the TV remote, telephone, keys, nicotine candies, forks, and spoons. Even though he keeps his telephone in a pouch in his wheelchair, he drops it when trying to use it due to his limited manual dexterity. For other tasks and objects, such as opening bottles and cans, putting on socks and shoes, and so on, he indicated that an assistive robot may be helpful. With respect to an interaction paradigm or interface, the patient feels that voice recognition would be preferable. He mentioned the need of the robot to follow his wheelchair. Thus, adding some kind of transmitter to the wheelchair would be necessary. When asked about any necessary additional features for an assistive robot, emergency monitoring has high priority.
- The third patient was an aged, Caucasian male (less than 70 years old), who was diagnosed with ALS 2 years ago. He was not able to walk or move his arms, only retaining the ability to move his neck and hand. He also used a power

wheelchair, but couldn't move his arm from his lap to the switch and joystick. His wife, the caregiver, needed to put his hand on the switch. They indicated that useful functionality for an assistive robot would not be grabbing objects, because he is not able to move his arm, but to grab his hand and move it to the switch. The caregiver also mentioned the need of moving his leg within the wheelchair. Additionally, scratching his nose or head may also be necessary. These needs reflect the requirement of the robot touching the patient, not just target objects in his living environment. Due to the limited arm movement, the laser pointer interface is unusable. The patient feels that voice recognition commands such as "put my arm to the switch" are essential. In order to assist with common tasks, such as drinking from a cup, the robot needs to hold a cup with straw close to his mouth. He also indicated that some patients cannot talk and need to use computer with eyes. A computer-based interface for initiating robot commands would be necessary for those individuals. For additional ideas of suggested functionalities for the assistive robot, they mentioned the needs of emergency monitoring and evacuation. For example, a robot can open the door or break the window if the house is on fire.

As seen in the case of the third patient, some patients in later stages of ALS do not see as much utility in object retrieval task support as initially anticipated. If the patient cannot grab or hold an object after the robot retrieves it, then the robot is of little use with additional caregiver help. This requirement then precludes the needs for an assistive robot at all. For patients at this level of impairment, novel inventions of robotic and other technologies are required to provide assistance.

Through the preliminary study, I found that ALS patients with different levels of impairment have vast differences in their potential needs from the assistive robot. In designing an interface to be used for the ALS patient population, seeking a universal solution seems not feasible. Rather, a customizable design with alternative modes

would be beneficial. Two patients currently use power wheelchairs and spend much of their daytime in the wheelchairs. Design of the assistive robot should consider its usage when the human operator is sitting in a wheelchair. All three interviewed patients attended the clinic with caregivers (mostly spouses), but there may be also patients who do not have such caregivers. In either case, relieving some of the tasks to be done by the caregiver would be very beneficial to alleviate some of the burden experienced by caregivers and moreover to provide independence to certain extent.

3.4 *Methods*

3.5 *Participants*

For the user needs assessment study, we recruited eight participants with help from the Emory ALS clinic during the clinics held twice in February 2008. At the clinic, patients undergo various tests and consulting services provided by a multi-disciplinary team of medical specialists, including neurologists, nutritionists, respiratory therapists, and so on. Due to these various services, patients usually spend several hours in the clinic and typically have free time between these services. A short introduction to the research project was given by a registered nurse or physician who provided treatment. If the patient indicated interest in participation, the interviewer entered the exam room and started the first step of the needs assessment. The recruitment process had no criteria for participant selection from the pool of ALS patients visiting the clinic except a preference for participants with verbal communication capabilities. For practical reasons, patients living relatively close to the Atlanta metro area were preferred. The demographic profile of participants is listed in Table 5. Although the relatively small number of eight participants is not representative of the overall ALS participation, the composition of ethnic and gender differences is in line with national statistics. In addition, the variability in disease progression and extent of physical limitations was representative of the general spectrum of ALS impairment.

Table 5: Demographic information

Variables	Values
Gender	Male (6), Female (2)
Ethnicity	White (6), African American (2)
Age	39 - 62 (average 53.5) years
Diagnosis	16.73 months ago (average)
Caregivers	spouses (5) family (2) paid personnel (1)

Table 6: Experimental protocol

Tasks	Description
1. Consent form	Participants were asked to read and sign the consent form.
2. Demographic survey	The participant was asked to fill out the demographic information sheet. Participants with difficulties in writing were assisted by the interviewer.
3. ALSFRS-R assessment	The Revised Amyotrophic Lateral Sclerosis Functional Rating Scale (ALSFRS-R) [44] was completed by the interviewer for each subject.
4. Photographing	Participants were asked to record any occurrences of dropped or unreachable objects via photographing and written logs covering the period of about one week.
5. Interview	Participants were asked to answer a series of open-ended questions relating to how they interact with objects on a daily basis.

3.5.1 Experimental protocol

The steps of the user needs assessment are outlined in Table 6. Tasks 1 to 3 were performed during the first initial meeting at the Emory ALS clinic. Task 4, the photographing of dropped or unreachable objects, took place in participants residences over the timeframe of a week. Either the ALS patient or the caregivers who help the patient took photographs and/or recorded on notepads. The last task of interviewing took place in the patients residences during a follow up visit.

3.5.2 ALSFRS-R

The ALSFRS-R (The Revised Amyotrophic Lateral Sclerosis Functional Rating Scale) is an assessment method used to determine the level of ALS symptom progression.

Table 7: ALSFRS-R assessment

Category	Assessment item
General	1. Speech
	2. Salivation
	3. Swallowing
	4. Handwriting
	5. Cutting Food and Handling Utensils (patients without gastrostomy)
	Cutting food and Handling Utensils (alternate scale for patients with gastrostomy)
	6. Dressing and Hygiene
	7. Turning in Bed and Adjusting Bed Clothes
	8. Walking
Respiratory	9. Climbing Stairs
	10. Breathing
	11. Dyspnea
	12. Orthopnea
	13. Respiratory Insufficiency

As shown in Table 7, this test assesses the physical condition of a patient based upon 13 assessment items scored from 0 (most severe impairment) to 4 (normal condition, without any impairment). The last 4 items are related with breathing problems and need to be tested by respiratory specialists, while the other 9 items are for general health assessment. The scores are added to generate an overall score. The ALSFRS-R score has often been used to predict the survival time of a patient and empirical study has demonstrated the efficacy of this score as a predictor of remaining lifetime [44].

3.5.3 Photographing of incidences of difficulty in object retrieval

To understand the personal experiences and needs related to assisted object retrieval, interview participants were given a digital camera to photograph instances in which objects are dropped and/or are otherwise unreachable. Participants were asked to photograph such instances over the period of a week. As shown in Figure 3.5.3, a Kodak C613 digital camera equipped with 1 GB memory card was provided and bound together with a pen and memo pad to record these events. The home survey,



Figure 25: Digital camera with take home survey

used to summarize events in which participant's experienced object retrieval difficulty, contained the following entries with examples:

- *Object:* Standard sized single volume spiral notebook, blue
- *Location:* Living Room
- *Orientation:* Fell flat on floor about one foot between both the edge of the sofa and myself.
- *Method of Retrieval:* Brother picked it up
- *Time Elapsed until Retrieval:* 30 minutes

3.5.4 Visit and interview

Following the photographing and notepad-writing period in the patient homes, researchers visited participants in their homes to ask questions on their experiences with object retrieval. The photographing session was also designed to help remind patients of these experiences although some participants could not take pictures because of their physical limitations. In instances where participants had taken photographs, questions regarding these photographs were first asked to better understand the situational context. The interview questions consisted of object identity, location, return method, and other as below.

1. *Drop Frequency*

- On a daily basis, how often do you drop objects?
- What objects do you drop most frequently?
- Do you ever experience tremors?
- Do you ever experience increased/sudden stiffness or weakness in your arms or hands?

2. *Object Identity*

- Of the objects you drop, which do you find most important to retrieve?
- Are there any objects that you avoid using out of fear of dropping them?
- What objects?
- Are there any everyday tasks that you can no longer do or have difficulty performing?

3. *Location Identities*

- In order to avoid impeding your mobility, what distance is required from objects and people?
- Are there specific places that make maneuvering more difficult than others?

4. *Method of Return*

- What is the most convenient way for you to receive from a caregiver?
- What locations are most accessible to you for retrieval?
- Between a caregiver returning or placing in a location, which is more valuable to you?

5. *Use of Laser Pointer*

- How familiar are you with laser pointers?
- Can the person hold the pointer?
- Can the person point the dropped object?
- How comfortable are you using a laser pointer?
- Is there an easier way for you to point objects?

6. *Other Questions*

- Is there someone to help you with daily chores?
- Would an object retrieving objects be valuable to you?
- How much would you like to spend for the robot?
- Do you have any specific devices to interact with objects?
- Can you imagine a task which you want a robot to help you?

3.6 *Results and discussion*

On the day of recruitment, a registered nurse at the ALS center conducted the ALSFRS-R assessment for each participant. The results of ALSFRS-R assessment show that the group of participants had considerable variability in the extent of disease progression. The summation score of the 13 ALSFRS-R sub-scores ranged from a minimum of 19 to a maximum of 37, with average value of 27 and standard deviation of 6.85. The following sections present the results from the two main activities of the study.

3.6.1 *Photographing*

Six out of eight participants took a total of 36 pictures of instances of object manipulation difficulty by themselves or with help with their caregivers. Because many of the participants had significant difficulty in upper limb mobility, the number of

pictures was more than my expectation. The pictures not only represented dropped or unreachable objects, but also general problems related to object manipulation. Therefore, pictures and notepad records of specific tasks, such as opening food containers and brushing hair, were also collected. The results of these data collection efforts were analyzed with the findings from the final interviews and are presented with representative pictures of objects, tasks, and environments.

As shown in Figure 26 to Figure 29, various objects were photographed by participants which actually presented difficulties in their daily lives with respect to object manipulation. Everyday objects, such as TV remotes and cellular/cordless phones, were initially expected during the planning of this study. As anticipated, participants dropped these objects on the floor and were faced with challenges to retrieve them. However, additional objects, such as the walking cane shown in Figure 28, were not anticipated. Generally, walking canes are used by individuals with considerable remaining lower limb ability who are not yet wheelchair bound. It was not expected that individuals who can walk with the aid of a walking cane to have significant difficulty in grabbing objects. However, as evidenced by the picture and records, some participants who are actually no longer able to walk still use a walking cane for other purposes. The participant who took the picture was using the walking cane to assist with grabbing objects on the floor with his foot. The walking cane presented a challenge to the current design of the robot because the gripper was not appropriate to grab long objects and objects that exceeded the limited weight capacity. As shown in Figure 29, small objects such as small screws, which a participant used for a hobby, and medicine pills were also reported to be dropped on the floor. These small objects represented another challenge for the robot application because many robot grippers are not designed to be used for very small objects such as medicine pills.

During the photographing session, we asked participants to record the elapsed time between when the object was needed and when they finally retrieved the object,

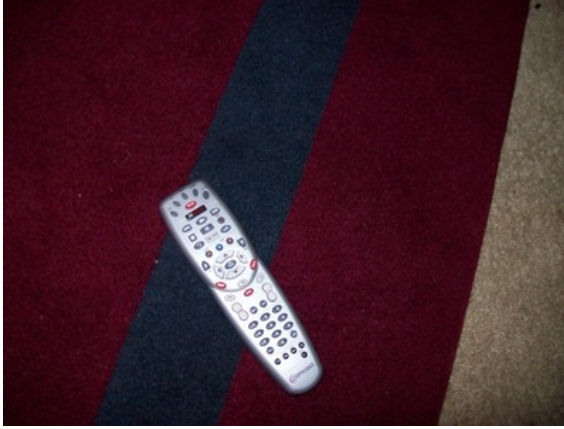


Figure 26: TV remote



Figure 27: Cell phone



Figure 28: Walking cane



Figure 29: Small screw

4

either by themselves or with help from caregivers. The collected time was used to help indicate the urgency for assistance with object retrieval. Six participants recorded more than one case, with 22 cases in total, of the elapsed time. Table 8 shows the resulting statistics.

In one case, a participant waited two hours for a caregiver to come. In the other case, a patient tried hard to retrieve without assistance and it took approximately

Table 8: Summary of 22 object retrieval times

Average	Min	Max	Stdev
9.4 minutes	1 minute	120 minutes	25.4 minutes

30 minutes to retrieve. The remaining 20 items took less than five minutes. This result implies that when a care giver is present in the participant's environment, object retrieval typically takes less than five minutes. Significantly long retrieval times were observed in the absence of a caregiver and the robotic assistance would be very helpful in this case. I hope robotic assistance can provide patients with a level of independence in order to limit the need for constant caregiver presence.

In addition to the pictures taken by the participants, the experimenter took additional pictures of the participants' home environments during the final interview. The physical environments surrounding the objects to be manipulated were the second target of photographs. Compared to controlled laboratory environments, actual places of residence where people live can present significant challenges to the mobility and object detection capabilities of the robot. Because the robot is built on wheels and possesses no walking capabilities, such as those demonstrated by the Honda ASIMO [76] (see Figure 30), stairs and uneven surfaces will present a limitation for the robot's movement. However, as shown in Figure 31 to Figure 34, most of the home environments visited were either flat or contained smooth slopes, so that those individuals in wheelchairs could move freely. Although the homes of the participating patients cannot fully represent all possible environments in which individuals with motor impairments might live, the observation of modifications to the living environments for wheelchairs suggests the likely viability of using mobile robots on wheeled bases.

However, the pictures also illustrate some potential challenges for the development of the assistive robot. The photo in Figure 31 was taken in the morning when bright sunlight lit the room. The sunlight was reflected by the tiled floor creating a bright glare. This type of highly reflective, bright environment will make it difficult for the robot to visually segment the object from the background. In addition, an environment that is too dark can also present problems, although this problem can be mediated by using an artificial light attached to the robot. Figure 32 shows a desk

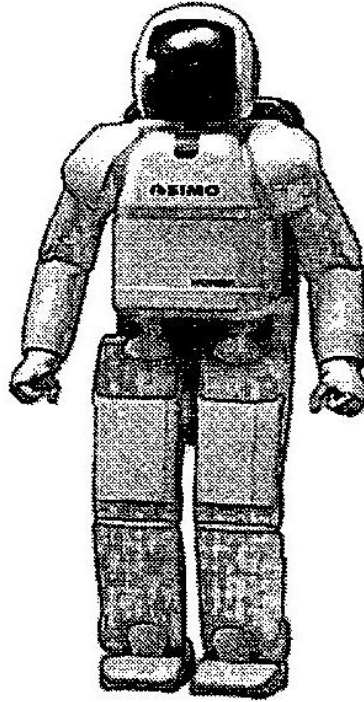


Figure 30: ASIMO robot [76]

with many objects placed in a cluttered fashion. Objects placed close to each other can confuse the robot, making it difficult to distinguish which object is actually the target object for retrieval, and making grasping more difficult. Floors with colored patterns such as that displayed in Figure 33 can also hinder object detection. Uneven surfaces, such as those created by flooring changes or floor mats (as shown in Figure 34) could slow the movement of the robot and decrease its accuracy. These identified challenges will be considered in further design and development efforts of the assistive robot.

Other than object retrieval, different tasks were also reported as difficult through participants' photographs and records. In Figure 35, the participant had difficulty in holding and moving a hairbrush due to limited hand dexterity. Similar to this, putting on socks, shirts, and shoes was one of the common tasks with which participants experienced difficulty. Opening food containers was also reported as a source



Figure 31: Shining sloped floor



Figure 32: Cluttered space



Figure 33: Patterned floor



Figure 34: Floormat

of difficulty for some participants as shown in Figure 36 because it requires significant strength to twist. Opening doors, as shown in Figure 37, and controlling light switches, as shown in Figure 38, were also difficult for some participants. Although the robot developed for this study focuses on the object retrieval task, these additional tasks and needs can provide direction for future assistive robot development efforts.

3.6.2 Final interviews

Final interview questions were structured into categories of objects, location, receiving method, laser pointer, acceptable performance, and other questions. As listed in



Figure 35: Brushing hair



Figure 36: Opening a jar



Figure 37: Opening a microwave door



Figure 38: Turning on/off a light switch

Table 9, participants frequently dropped objects (e.g., on a daily basis) and tried not to use breakable or heavy objects for fear of dropping them. The most common objects were phones and paper materials, the latter of which may be difficult for retrieval with the current robot design. Phones and walking canes were rated high with respect to retrieval importance. Participants experienced difficulty and/or were no longer able to perform tasks such as dressing, bathing, and carrying heavy objects. These areas need to be further investigated to identify possible robotic solutions to help individuals with motor impairments with these tasks of daily living.

Questions and answers related with location issues are listed in Table 10. The

Table 9: Answers to object related questions

Questions	Summary of answers
Frequency of dropping	5.5 times per day(average)
Frequently dropped items	Phone/cellphone (4) Magazines or newspaper (3) TV remote 3 Pills, fork, pens (2) each
Most important to retrieve	Phone or cellphone (2) Walking cane (2) key, pencil, fork(1 each)
Avoided objects	Breakable things (glasses, dishes) (4) Heavy things (laptop) (2)
Difficult tasks	dressing (buttoning, wearing socks) (2) personal hygiene (2) Carrying, transporting (2)

Table 10: Answers to location related questions

Questions	Summary of answers
Places difficult to maneuver	Shopping (2)
Transporting in a room	very useful (8)
Transporting between rooms	very useful (8)
Opening doors	very useful (7)
Traveling with users	very useful (8)

ability of the robot to follow the user into a room, between rooms, opening doors, and traveling in automobiles were perceived as useful. Increasing the mobility and portability of the robot would be one future direction of assistive robot development. Participant answers regarding the preferred receiving method, presented in Table 11, illustrate a split preference between direct handing to the user and putting the object on the nearby surface. These mixed results may be dependent on the exact context of the object and situation. Therefore, developing technologies for both methods of returning objects to the user would be preferable.

Because the primary interface for controlling the robot involves the use of a laser pointer to indicate the target object to be retrieved, the interviewer brought a laser

Table 11: Answers to receiving method questions

Questions	Summary of answers
Best handing method	Holding (3) Put to the hand (3) Putting on a surface: (2)
Good place to put	Tables (8)
Preferred method	Caregiver (4) Surface (2) depends on objects(2)

pointer and asked participants to practice using it. Although it was difficult and took time for some participants, all participants were able to successfully hold the laser pointer. However, two individuals failed to effectively point the laser pointer and only three participants indicated comfortable use. Some participants complained that the laser pointer was too heavy, but also too small - especially the button used to activate the laser. It became clear that design modifications of laser pointer would be necessary. We observed significant difficulty with holding and aiming the laser pointer, which suggested the need to minimize requirements of hand mobility. A head-mounted laser pointer was suggested by one participant, which seemed ideal as all participants could move their head freely. An ear-mounted laser pointer, as shown in Figure 39, were developed as a result of these findings from the needs assessment and can be hooked on the ear of the user and directed by head movement rather than hand movement. The laser pointer is also lighter than a standard laser pointer because of customized casing made from a 3D laser pointer and has a bigger push button according to the user needs.

We also asked participants about acceptable performance measures in terms of error rate, task completion time, and learning time in order to roughly estimate their expectations of the robot system. Although most participants had difficulty in estimating their exact limits of acceptable performance, their answers - outlined in Table 13 - show that they were relatively error tolerant in case the robots are

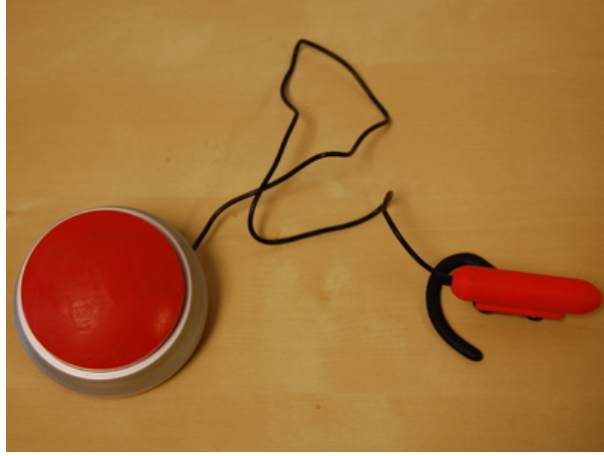


Figure 39: Ear-mounted laser pointers

Table 12: Answers to laser pointer related questions

Questions	Summary of answers
Holding laser pointer	yes (8)
Pointing a laser pointer	yes (6)
Comfortable	comfortable (3) neutral (1) uncomfortable (4)
Better method	bigger pointer and bigger button fixed and swerving pointer head mounted pointer

Table 13: Answers to performance related questions

Questions	Summary of answers
Error rate	less than 20% (3)
Time	0.5 to 5 minutes with less than 2 minutes (3)
learning time	0.5 hour - 2 month (very diverse)

effective. The expected task completion times were generally within 2 minutes, which was shorter than the completion time of the robot at the time of the study. Although it is clear that we need to increase the speed of the robot, most users agreed on the effectiveness of the robot even though it took longer time to complete the task when they actually tried to use the robot in the lab experiments. There was considerable variability in learning time, although the actual learning time for using the robot was not expected to exceed 30 minutes due to the low complexity of the controlling interface and nature of the tasks.

Table 14: Answers to other questions

Questions	Summary of answers
Caregivers	All day (5), Partial(3)
Valuable	Yes (8)
Acceptable cost	less than 2000 US Dollars (4)
Own assitive instruments	gripper stick (2) (not very helpful) sticky plastic pad, good to prevent slippery
Future tasks	buttoning shirts (2)

Participant answers to additional questions are listed in Table 14. All participants agreed that an object retrieval robot would be valuable. Although all participants had someone to help them with their daily chores, three participants had to stay at home without any additional human assistance. The question of acceptable cost was difficult to answer because participants were not able to accurately assess the effectiveness of the robot. However, the answer of less than 2000 US dollars represents a value significantly lower than the realistic cost of the robot system in the near future. Insurance compensation for assistive robots, as practiced in Europe [75], will be necessary until advances in technology lower the cost. Robots, such as that depicted in Figure 40, can reduce the price significantly due to the simple structure focusing on specific tasks. Dressing tasks, such as buttoning shirts, were found to be an important area of future development. The last question, not shown in Table 14 because answers were descriptive, focused on the participant opinions regarding the expected benefits of a mobile robot versus one that is wheelchair-mounted. The projected strength of the mobile robot would be the increased capability of fetching objects remotely located from the user, such as objects placed other rooms. However, wheelchair-mounted robots were seen as helpful because it will always be close to the user.

3.6.3 Applying results of the needs assessment

Continuing the efforts of the needs assessment, we identified the need of creating and validating a list of objects which individuals with motor impairments thought were important for robotic assistance. The validated list would be helpful to evaluate the developed robot under meaningful, realistic conditions and prioritize the limited time and resources for research. Based on the objects found in the needs assessment, we created initial 40 objects which were potentially important for retrieval [10]. We interviewed 25 ALS patients from the Emory ALS clinic to help prioritize the list by giving scores based on perceived importance and asked if they had additional objects not included in the list. The resultant prioritized list was used for evaluating assistive robots developed in our lab including EL-E and Dustpan [102].

The ultimate purpose of the needs assessment study was to inform the design decisions in the continued development of the assistive robot. Ideally, the reflection of user needs in the design decisions should be included as early as possible in the concept generation phase of development. In fact, at the time of this user needs assessment study, the robot was in the prototype stage. As such, design changes from the results were much less costly than if further design decisions had been previously implemented. However, the development project must embrace constant changes in the robot's capabilities due to the continual technological development and innovative ideas that arise in robotics. Therefore, the design of the robot system continues to be open to change and any remaining design decisions will incorporate those facts and insights gleaned from the user needs assessment.

The results of the user needs assessment is anticipated to influence the assistive robot design in the following specific areas:

- *Interfaces not requiring upper limb mobility*

Many of the participants had difficulty in moving arms and hands accurately.

If the controlling interface design is dependent on the upper limb strength and

dexterity of users, the usability and applicability of the interface across the spectrum of users with motor impairments would be limited. Interfaces requiring minimal strength and dexterity of hand/arm movement would be preferable. Prototypes including an ear-mounted laser pointer and touch screen interface were developed following this needs assessment. Because ALS patients lose mobility of upper arms and the neck eventually, an additional interface utilizing eye movements was predicted to be an additional, viable option as an end-stage interface for many users, representing a solution that will remain useful throughout the continual limitation in their motor capabilities.

- *Design of the robot gripper apparatus*

A gripper refers to the hand of a robot, which directly touches objects to be picked up. The gripper of the current implementation is a simple two-finger shape. Although it was able to pick up many types of everyday objects during the preliminary lab-based experiments, there might be different kinds of objects which need to be picked up by actual users in their everyday lives, that the current gripper may not be able to handle effectively. For example, the current gripper has difficulty in picking up small and flat objects. Figure 40 is an alternative gripper design, currently under development, that may deal with some of these limitations [102]. The end effector slides a thin, and flat panel under the object to be grasped and pushes the object with a compliant finger. Then, the arm lifts the object off of the floor.

- *Load capacity and operating speed*

The payload capacity of the robot depends on the gripper, manipulator, and vertical linear actuator. Although it is impossible to accommodate all possible objects with all possible weights, the collected data on typical objects can determine the target maximum handling capacity of the robot.

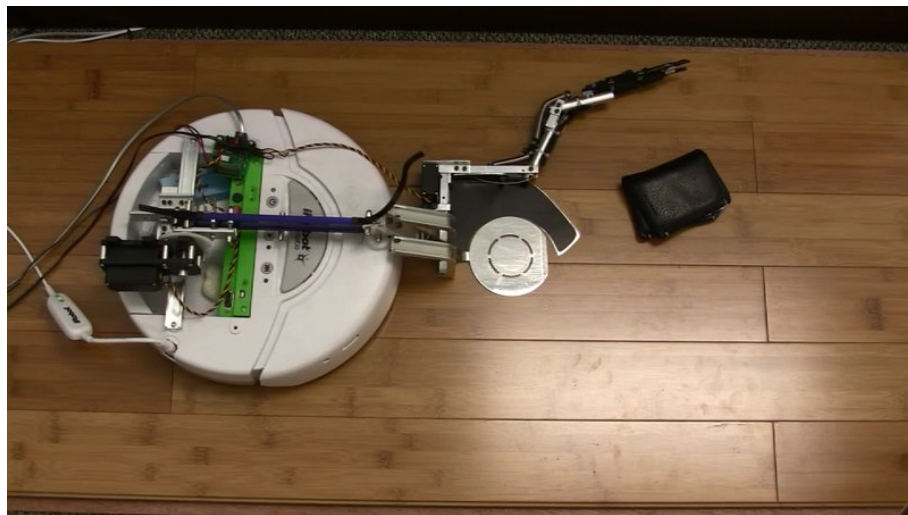
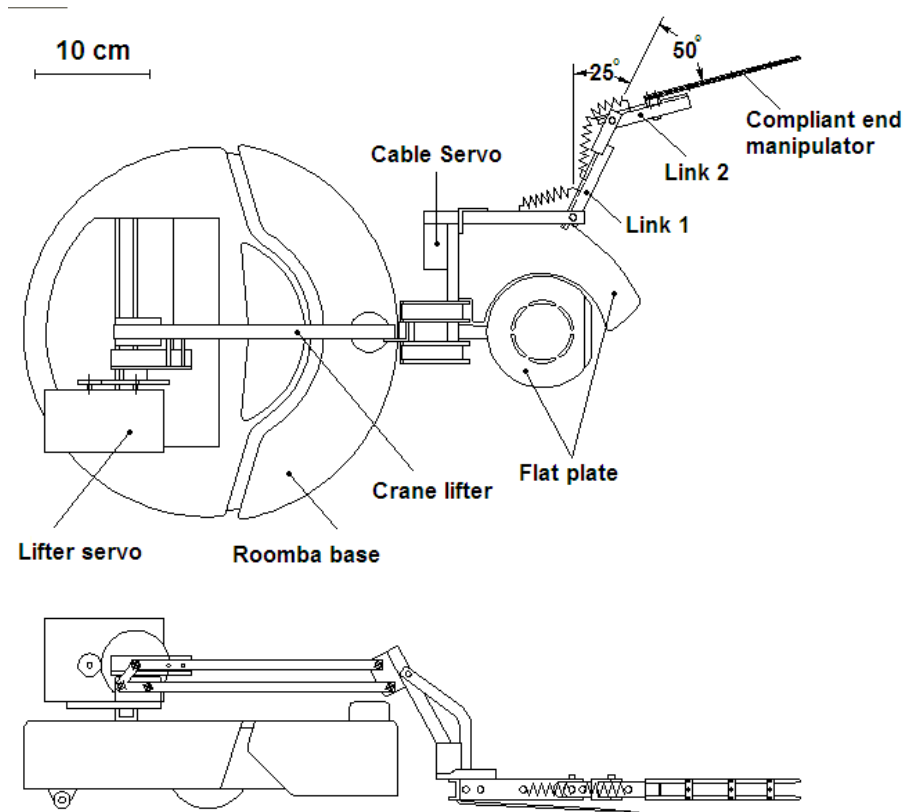


Figure 40: The “Dustpan” robot

- *Vision processing requirements*

The object detection task is dependent on the robot’s vision processing of the laser pointer’s light which reflects off of the surface of the objects to be fetched. The colors, shapes, and materials of the objects may affect the effectiveness of the vision processing in object segmentation. The existence of other objects blocking the target object, as well as specific environmental lighting conditions, may also present additional challenges in vision processing.

3.7 Conclusions

This user needs assessment study was important for the research team to understand the unique daily living difficulties that ALS patients experience due to their progressive loss of motor capabilities. The results provided valuable insight into potential tasks, target objects, and environmental limitations that may need to be addressed in the design of the assistive robot. This user-centered design process was important for understanding the complexity and variability of the object retrieval task, to be performed within the actual living environs of individuals with motor impairments. In addition, we also received important insights into the patients’ attitudes and expectations of the capabilities and performance of the robot.

- **Objects**

Various household objects of variable size - from a small medicine pill to an adult-sized walking cane - are necessary to be retrieved and should be able to be handled by the assistive robot. Based on the frequency with which objects were dropped, in addition to the non-retrieval tasks identified by participants as areas of needed assistance, there is a clear opportunity for robotic-based aid for individuals with motor impairments. This is particularly true in cases where the individual does not have a constant, live-in or always accessible caregiver. On average, objects were dropped with a frequency of 5.5 times per day, with an

average 9.4 minutes retrieval time. They expected the robot perform a retrieval task within 5 minutes with less than 20% error rate.

- Environments

The patients home environments of patients possess diversity in clutteredness, lighting conditions, and floor materials which should be considered in the robot design. However, many home environments consist of flat surfaces to accommodate use of a wheelchair. This modified environment is promising for robots on a wheeled platform for indoor use rather than walking robots.

- Attitudes

All participants agreed on the potential value of and interest in an assistive robot capable of object retrieval and generally thought the mobility and portability of the robot are important. Additionally, participants thought it was important for the robot to be mobile, moving in a room, between rooms, and following while they drive.

- Laser pointers

In trial uses of a hand-held laser pointer as a robot interface, six out of eight participants could point to an object. However, only three participants were comfortable in using it. This implies that although standard hand-held laser pointers are very effective for people without motor impairments, their design needs to be modified to achieve usability for individuals with severe motor impairments. For our user evaluation studies, we developed ear-mounted laser pointers to address this need.

The needs assessment study also provided immediate and interesting information regarding the changes needed in the design of the robot, including the end effector/gripper design, the robots mobility, and the design of controlling interface. All

of this information will be extremely helpful for directing the future design and development efforts for the assistive robot system. We hope these results help other researchers looking at assistive robotic manipulation to develop technologies that will help individuals with motor impairments achieve relative independence in their daily lives.

CHAPTER IV

RANKED LIST OF EVERYDAY OBJECT FOR ROBOTIC RETRIEVAL

Robots that traverse unstructured domestic environments and manipulate everyday objects are beginning to become a reality in labs around the world. To date, however, there is a lack of agreed upon benchmarks for evaluating robotic systems for mobile manipulation. Unlike the speech and vision communities, robotics researchers have yet to define common benchmarks by which they can evaluate the performance of their systems. A key question for robotic researchers focused on manipulation in domestic environments is: *What objects are important to manipulate?*. We believe this is exactly the type of question that research on human-robot interaction should answer.

In this study, we propose a ranked list of 43 everyday objects for the evaluation of assistive mobile manipulation systems operating in domestic settings. We have used the method of user-centric design to create and validate this list with a representative motor-impaired population, specifically patients with Amyotrophic Lateral Sclerosis (ALS). ALS was chosen because the progressive nature of the disease leads to a broad spectrum of motor impairments, which can be representative of those impairments experienced by other populations (e.g., the elderly).

This study included an initial needs assessment involving eight patients and a follow-up survey (using the Likert scale) involving fifteen patients. We also presented the ranked list and an associated website where a standard set of representative objects can be purchased online for use by other researchers examining the development of assistive robots. Finally, we conclude with an example of evaluating a grasping

system using nine of the ten top-ranked objects.

4.1 *Motivation & introduction*

As previously mentioned, assistive robots are being developed and evaluated in research labs, although there are few established standards for grounding the evaluation. Unlike the speech and vision communities [24, 58, 72, 29], robotics researchers have yet to define common benchmarks by which they can evaluate the performance of their systems. A key question for robotic researchers focused on manipulation in domestic environments is: *What objects are important to manipulate?*. By developing benchmarks tailored to specific application domains and user populations, researchers have the opportunity to ground their research and answer the otherwise subjective question: *What is important?*. Moreover, benchmarks of this nature can enable researchers without direct access to user populations to contribute to progress in a validated way.

In this study, we focus on the application domain of assistive object retrieval and a user population of ALS patients from the Emory ALS Center. ALS is affecting around 30,000 Americans [86] that leads to a broad spectrum of motor impairments indicative of impairments experienced by other populations. Overall, more than 24 million Americans possess some form of physical disability that hinders basic physical activities, implying that assistive robotics has huge potential to benefit society. With approximately 250,000 people with spinal cord injuries [67], 4,700,000 stroke survivors [87], and 30,000 ALS patients [86] in the US alone, assistive robotics have the potential to make a profound, positive impact.

Moreover, as is often noted, the proportion of the worldwide considered elderly is substantially increasing, with over 16,000,000 people currently over the age of 75 in the US [90]. This aging population creates a large scale need for affordable, robust, robotic assistance. In the US, 20% of people between 75 and 79 years of

age have been shown to require assistance in activities of everyday living, and this percentage increases precipitously with age, with 50% of people over 85 years of age requiring assistance (from US census data [90]). Many people with motor or mobility impairments could benefit from robotic assistance in a broad spectrum of activities of daily living, including object fetching, object carrying, personal hygiene, food preparation, and the operation of drawers, cabinets, and doors [82].

We focus on object fetching because it is a foundational capability for mobile manipulation. Many desirable assistive tasks, such as putting away the dishes, cleaning a home, administering medicine, and picking up dropped objects fundamentally involve pick-and-place operations in unstructured domestic settings. As such, assistive object retrieval is both a highly valued assistive application on its own and a step toward more general capabilities.

In this context, a clear first step for benchmarking object fetching is to identify objects that motor-impaired users would like or need a robot to retrieve. Through a needs assessment and an object-centric survey of ALS patients, we have developed a ranked list of 43 everyday objects. An important outcome from this study is the object list and a website with a matched list of objects that can be purchased through online vendors, so that researchers can work with the same set of objects and compare results: http://www.hsi.gatech.edu/hrl/object_list.shtml. We also describe an example of evaluating a grasping system with nine of the top ten objects from the resulting list of objects.

4.2 *Related works*

This work provides assistive robotics researchers with a set of easily-purchasable objects that allow more targeted system development and evaluation. In a broader sense, the work provides the perception and manipulation communities with a set of objects, with immediate practical utility, that can inform sensing, algorithms, and planning.

We address the related work for these two audiences separately, though they are not necessarily mutually exclusive. Existing work from both audiences generally suffers from one or more of the following drawbacks during evaluation:

- ***Insufficient Number of Objects:*** There are many examples where a system is evaluated using a very small set of objects [31, 9]. While this may demonstrate a new, specific capability, it is often difficult to evaluate the generality of the method.
- ***Insufficient Variation in Object Type:*** Human environments are full of distinctive objects. Frequently, the objects selected for evaluation represent only a small portion of the natural variation found across objects in domestic settings [23, 95]. For example, while the ability to work with cans, bottles, and other rigid cylindrical objects is crucial, common objects found in human environments are much richer in variation.
- ***Objects Without Justification:*** This tenet is central to the focus of this study - providing a justification for the objects that are evaluated. Most researchers have applied a “grab-bag” approach to object selection. Without a clear method by which to select objects for evaluation, researchers can be tempted to cherry-pick objects that are well matched to their robot’s capabilities. Whether conscious or unconscious, this selection bias reduces reproducibility, works against negative results, and can distort perceptions of actual system performance. Moreover, it obscures the path for progress by hiding the areas most in need of improvement. This inhibits the ability of researchers to build on the body of published research and restricts progress towards complete functional systems robust enough for real-world operation and user satisfaction.



Figure 41: Examples of novel objects taken from [89].

4.2.1 Object manipulation by mobile robots

Much of the research on robots for assistive mobile manipulation has focused on wheelchair-mounted robot arms controlled via teleoperation, such as the MANUS arm [20] and FRIEND-I [95], amongst others [89]. There has recently been a surge of interest in autonomous mobile manipulation in domestic environments [51, 49], such as El-E in Figure 42 [9]. At this time, there are no clear standards for the evaluation of manipulation capabilities of assistive robots with autonomous manipulation capabilities.

At this time, the evaluation of a robot’s capabilities through empirical testing often plays a lesser role in technical communications relative to the implementation details, theoretical analyses, and results in simulation.

As the state of the art becomes progressively more capable, comparative evaluations using compelling and practical standards for benchmarking promise to add value to the community and, in turn, have the potential to benefit actual user populations, such as the motor impaired - be it ALS patients, stroke victims, or the elderly.

Researchers of rehabilitation robots and orthosis have recognized the need of providing aid to people with motor impairments. In the development of the technology,



Figure 42: ALS Patient (*left*) using laser pointer interface to control El-E (*right*) – photo used with patient permission and IRB approval.

researchers have undertaken several surveys and user studies with patient groups [82, 73, 34] in order to better understand which areas and tasks of daily living have relative priority. Previous research has identified task areas, such as eating & drinking, personal hygiene, and object fetching & retrieval as targets for assistance. While these existing surveys and user studies focused on determining which tasks to focus on, we also need to understand the detailed needs of prospective users, such as finding out which types of objects are important for retrieval. Towards this goal, we conducted the user needs assessment and the study of prioritized object list with ALS patients presented in this study.

4.2.2 Grasping everyday objects

As robots are put into ever more unstructured human environments the variations become wider and more challenging [48]. Object grasping is a fundamental capability for object retrieval. There is a long history of research on robotic grasping, but relatively few researches have focused on grasping everyday objects in domestic settings. Some of the grasping literature focuses on grasping simulated objects with simulated robots [65]. For our application, robots must ultimately work with real objects and

real people. Therefore, we give priority to performing evaluation with real objects. Within this section, we discuss two examples of recent research studies focused on grasping everyday household objects. Both studies represent state-of-the-art research with excellent performance on their chosen objects. It is informative to note the great disparity between the objects they used for evaluation.

While there are a number of works that use just a few objects [23], the algorithms that show generalization are most relevant to this document. A number of researchers have addressed this new realm with algorithms for perception and manipulation.

Saxena and Ng [77], have developed a system that learns grasp points via visual features from synthetic images. They evaluated the resultant implicit model by performing grasps on 18 novel objects, including a clear glass, a coffee cup, a roll of tape, a coffee pot, a toothbrush, a lint roller, a cellphone, keys, a plastic box, a box cutter, binoculars, plates, markers, and jugs. These objects were chosen in a “grab bag” fashion. Further, the evaluation does not clearly consider other crucial environmental factors with major ramifications on the vision processing, such as object orientation, placement, and backgrounds.

Another representative example from Sweeney and Grupen [84], demonstrates successful implicit model generation that enables grasp evaluation on 31 different objects. Again, the objects were chosen in a “grab-bag” fashion. Additionally, all of the objects were rigid, and most were either cylindrical or cubic. More significantly, the backgrounds were of a single color and of uniform texture to allow “green screen” like processing to segment the foreground. This assumption and limitation was stated up front.

In a broader sense, the work elucidated herein provides the perception and manipulation communities with a set of objects, with immediate practical utility, that can inform sensing, algorithms, and planning. The evaluation methods will also prove valuable as they provide a disciplined way of varying environmental parameters such

that unbiased comparisons can be made between related works.

4.2.3 Categorization of objects

The central challenge of unstructured human environments - copious environmental variation - encompasses the variations in objects themselves, which vary considerably in their material, size, shape, weight, color, and so on. Each variation has ramifications for sensing and/or manipulation. For example, consider the following examples:

- ***Rigidity***: A large body of work has focused on manipulation of rigid objects [48, 107]. However, soft, deformable or non-rigid objects, pose a unique set of challenges. Deformable objects are often difficult to explicitly model with high fidelity. Approaches such as edge detection and passive tracing to manipulate deformable objects such as clothes have had some success [35].
- ***Transparency and Reflectivity***: Vision is one of the most ubiquitous sensors for robots. Extensive effort has been expended to advance the capabilities of imaging under non-ideal conditions - such as transparent or reflective objects. Many robots, such as Stair [77], use vision to inform grasp controllers that can cope with translucent or transparent objects.
- ***Color and Texture***: Color and texture are common visual features that vary wildly across objects. These crucial features are used by many robots, such as El-E [69], in informing grasp controllers and perception. The color and texture features also have ramifications for laser range finders, as black objects have been known to cause faulty range readings.
- ***Weight***: Gripper payload is a crucial design choice, as it ultimately determines which objects a robot can manipulate. This is a classic design tradeoff between high-payload, low-sensitivity versus low-payload, high-sensitivity that dictates the ability to either lift large loads or manipulate fragile objects.

- ***Size***: Size constraints are generally linked to object weight, and thus manipulator payload. For example, robotic systems employing high-payload prehensile end effectors, grasping small objects (such as individual pills) can be exceedingly difficult. Small objects often require alternative non-prehensile end effectors such as suction, while large objects require manipulation methods such as pushing [6] or pivoting [106].
- ***Shape***: In addition to the size, shape can have severe implications on manipulation and sensing. For example, a credit card, laying flush on a table is virtually invisible to laser range finders. Furthermore, it poses unique challenges to prehensile manipulation, hence the development of custom end effectors, such as [102], which operates by analogy to the human fingernail.

Users are generally ambivalent to the challenges imposed on sensing and manipulation by an object’s physical characteristics; the user just wants the robot to work with *their* objects. While some motor-impaired individuals may be amenable to modifying their environment (such as wheelchair users adding ramps to their homes), the goal of large-scale deployment of home robots will require robots to address broader needs with less user imposition. By providing a list of everyday, home objects with immediate practical utility (selected agnostically with respect to sensing, manipulation, and algorithms), we hope to provide researchers with a tool to address the goal of ubiquitous home robots.

4.3 *Creation of the list*

As described in the previous chapter, we initially conducted a user needs assessment with 8 ALS participants via an ongoing collaboration with the Emory ALS Center. We gave an instrument containing a journal pad, pen, and a digital camera to participants and asked them to document each occasion when “object manipulation was difficult or impossible” by keeping a week-long journal taking photographs to record their

Table 15: Objects in the needs assessment

Questions	Summary of answers
Frequently dropped items	Phone/cellphone (4) Magazines or newspaper (3) TV remote 3 Pills, fork, pens (2) each
Most important to retrieve	Phone or cellphone (2) Walking cane (2) key, pencil, fork(1 each)

experiences. Several challenges were universal in the surveyed population: (1) fetching dropped objects, (2) opening doors, (3) changing clothes, and (4) brushing teeth and hair.

From the photographs and final interviews, we found that dropped objects were a significant problem throughout the course of the day, especially during times when a caregiver was not immediately available. Objects remained on the floor from 1 minute to 2 hours, depending on caregiver availability. As listed in Table 15 certain objects were more highly sought after than others - specifically cell phones, cordless phones, medication, and TV remote controls . The results from this initial study illustrated the need for a more comprehensive list of everyday, objects from the home to direct our further design and evaluation efforts.

4.3.1 Initial Set of Objects from the Needs Assessment

Based on this needs assessment we created an initial set of objects indicated to have importance to our user population.

- **Medical:** Medical objects include medication bottles and boxes, as well as pills. Unfortunately, this is a critical category for users with motor impairments, whether due to ALS or aging. These objects were one of the most referenced objects in the preliminary needs assessment; hence, they have been placed in a category all their own.

- ***Dining Room***: Unsurprisingly, most of the objects in the dining category relate to eating, such as kitchen utensils, food/drink containers, etc.
- ***Bathroom***: Bathroom objects are distinct from others in that they focus almost exclusively on personal hygiene.
- ***Personal Belongings***: This category constitutes items that remain in near proximity when staying at home
- ***Living Room***: Anecdotally, we found that motor impaired individuals spend a dominant portion of time in the living room. Living rooms are dominated by large objects such as sofas, couches, tables, and televisions, which are not manipulated directly, but rather have objects of interest placed atop or beside them.
- ***Bedroom****: Most of the dropped items of consideration in bedrooms relate to articles of clothing.

We did not include clothes from the bedroom items but added them later at the behest of participants. Table 16 shows the object list.

4.3.2 Patient Interviews to Rank Objects

In total, 25 ALS patients (Note: participant demographics shown in Table 17) participated in 30 minute interviews. We recruited seventeen patients during visits to the Emory ALS Clinic. Nurses at the clinic first introduced the research. The interviewers entered the room and interviewed the patient only if the patient showed interest and agreed to participate. To motivate participants, we briefly introduced the goals and existing functionality of EL-E with respect to assistive object manipulation. The remaining eight participants' interviews occurred during visits to the Healthcare Robotics Lab, where they worked with EL-E as part of another evaluation study.

Table 16: Initial List of Objects

Category	Objects	
Medical	Prescription Bottle Medicine Box	Pill
Dining	Non-Disposable Bottle Cup / Mug Plate Can Spoon Knife	Disposable Bottle Plastic Container Bowl Straw Fork
Bathroom	Toothpaste Hairbrush Hand Towel	Toothbrush Soap
Personal Belongings	Purse Coins Keys Wristwatch Credit Card Pen / Pencil Walking Cane	Wallet Bills Cellphone Lighter Glasses Scissors
Living Room	Cordless Phone Book Newspaper Small Pillow	TV Remote Magazine Mail
Bed Room*	Shirt Socks	Shoe / Sandal Pants

Table 17: Demographic Information For Interview Participants

Variable	Values
Gender	Male (15), Female (10)
Ethnicity	White (15), African American (10)
Age	37 - 81 (mean 58.6) years
Diagnosis Duration	3 - 120 (mean 30.3) months

The interview began by reading consent forms to the participants and receiving their signatures. In instances of writing difficulty, a caregiver signed on behalf of the participant. A demographic survey followed this initial recruitment and orientation session.

In accordance with the obtained IRB approval, a questionnaire was given that asked

participants to indicate the relative importance of each object in a list (with the representative pictures in Table 18), based on a 7-point Likert scale. The questionnaire follows.

For a research project at Georgia Tech and Emory, we are developing a robot to help people to manipulate everyday objects. We are trying to find a list of common objects to be useful in robot manipulation research for us and other robot researchers. Your help from experience would be essential in creating a validated list.

Following is a list of objects with pictures which might be important to be retrieved by a robot if they are dropped or unreachable in your daily lives. For each object in the list, please give a number from 1 to 7 by following criteria for the importance of retrieval based on your experiences.

7	Very Important
6	Important
5	Slightly Important
4	Neutral
3	Slightly Unimportant
2	Unimportant
1	Very Unimportant

The interviewer read these instructions to the participant and explained how to rate the relative importance of these objects with respect to assistance with object retrieval. Then the interviewer showed the images of objects printed on the documents and requested the participant's rating on the 7 point Likert scale shown above [3]The participant would either verbally indicate the rating, or point to it if speech was too difficult.

An open-ended followup question concluded the interview.

In your experience, if you have objects which were not included in the above list but you think are necessary to be retrieved by a robot, please list them.

The ten interviews were followed by a preliminary results analysis. The analysis revealed that half of the participants inquired about articles of clothing such as socks, pants, and shirts. Originally, clothing was omitted from the initial object list, based upon our experiences from the needs assessments. As ALS patients were expected to have great difficulty dressing, even if clothes were retrieved by a caregiver (or robot), it was anticipated that these were not necessarily useful objects to target for assistive robot retrieval (as a human caregiver would still need to be present to aid with the dressing process). At the behest of participants, the clothing items were added to the list for the final fifteen interviews.

4.4 *Results*

By averaging the Likert-scale rating of each object across all participants, we derived a numerical ranking of objects. Based on the responses of ALS patients, we can consider highly ranked objects to be more relevant (and broadly applicable) to robotic assisted object retrieval compared with lower ranked objects. The results of this ranking (with averaged Likert score) is shown in Table 18. A low ranking does not detract from the importance of an object (even those not present on the list); rather, it provides researchers with an indication of which objects are *most* important so that research efforts can be focused for *maximal* impact.

Among the 43 total objects, 40 objects were rated by all fifteen participants. Three additional objects (socks, shirt, and pants) were added based on consensus about “additional objects” in session one, and then rated by the five participants in session two. While some participants thought the list was comprehensive, others suggested additional objects through the open-ended followup question. However, there was no consensus on further omissions. Some of the other objects mentioned were glass cups, milk jugs, coffee pots, tissues, and bath towels. Two patients also mentioned “*myself*” as an additional object, which represents the desire of patients with motor impairments to have a robot that can move their body or parts of their body for them. In our initial needs assessment, this desire also came up frequently. Robots that can grasp and change the position of body parts (legs and arms) or the whole body would be extremely useful for this patient group. Although this is clearly important, we are treating this as a separate category of manipulation that is distinct from object retrieval, as represented by the prioritized list of objects.

However, the safety issues (and associated IRB complications) regarding direct contact between the robot and the user must first be resolved. However, we do view this as an important research area for robotic manipulation. While initiatives such as Vecna Robotics’ Bear [93] attempt to address robots capable of moving people, we

Table 18: Prioritized List of Object Classes














Rank	Object Class	Image	Rating Mean	Rating Stdev.	Weight (grams)	Max size (cm)	Rank	Object Class	Image	Rating Mean	Rating Stdev.	Weight (grams)	Max size (cm)
1	TV Remote		6.64	0.57	90	18	22	Credit Card		4.96	2.37	5	8.5
2	Medicine Pill		6.36	1.55	1	2.2	24	Medicine Box		4.88	1.88	25	10
3	Cordless Phone		6.28	1.31	117	15	24	Bill		4.88	2.26	1	13.5
4	Prescription Bottle		6.08	1.31	25	7	26	Straw		4.80	2.22	1	20
4	Fork		6.08	1.12	39	18	26	Magazine		4.80	2.02	206	27.5
6	Glasses		6.00	1.53	23	14	28	Plastic container		4.72	2.16	49	13
7	Toothbrush		5.96	1.81	15	19	29	Newspaper		4.60	2.16	247	31
8	Spoon		5.92	1.19	38	17	29	Non-disposable bottle		4.60	2.00	709	20
9	Cell Phone		5.88	1.69	76	9	31	Pants		4.53	2.47	539	100
10	Toothpaste		5.72	1.84	160	20	31	Shirt		4.53	2.47	229	66
10	Book		5.72	1.46	532	24	33	Wallet		4.48	2.33	116	100
10	Hand Towel		5.72	1.46	65	58	34	Small Pillow		4.44	2.08	240	38
13	Mail		5.60	1.98	22	24	35	Socks		4.40	2.08	41	23
14	Cup / Mug		5.56	1.76	267	12	36	Hairbrush		4.36	2.46	100	24
15	Soap		5.44	2.08	116	9.5	37	Can		4.32	2.08	350	6.4
16	Disposable bottle		5.40	1.66	500	13	38	Coin		4.16	2.51	6	2.5
17	Shoe		5.36	1.98	372	30	39	Walking Cane		3.76	2.47	1140	94
17	Dish Bowl		5.36	1.66	154	13	40	Wrist Watch		3.52	2.35	86	10
19	Keys		5.28	2.28	24	8.5	41	Scissors		3.40	2.33	25	14
20	Dish Plate		5.24	1.85	182	18	42	Purse / Hand-bag		2.84	2.29	380	24
21	Pen / Pencil		5.04	2.13	3	14	43	Lighter		2.04	1.99	91	6
22	Table Knife		4.96	1.95	76	24							

Table 19: Summary by object group

Group	Score	Shoft	Trans- parent	Weight	Size Short	Size Long
Very important	6 – 7	0	2	51.2	2.1	11.2
Important	5 – 6	3	2	133.4	1.8	19.0
Slightly Important	4 – 5	5	1	281.7	2.8	43.0
Not Important	1 – 4	0	0	196.5	4.2	15.2

view this category as beyond the auspices of the current study, which focuses on the dropped object list.

We divided the objects into 4 groups based on the score as in Table 19. One interesting observation that resulted is that the group of objects receiving the highest scores primarily consists of rigid objects and those that are generally smaller and lighter. Specifically, the smallest object the medicine pill - is in this group. Meanwhile, other objects groups with lower scores include soft objects, such as paper or clothing, and heavier items, such as certain clothing items and the walking cane. Transparent objects are also included in the first three groups. This observation could potentially help researchers when designing a robotic system. For example, prioritizing the manipulation of small, light objects compared to larger, heavier objects would cover many of the highly ranked objects.

4.5 Conclusion

A key question for robotic researchers focused on manipulation in domestic environments is: *What objects are important to manipulate?*. Within this chapter we have provided one answer to this question, albeit conditioned on a specific application and user population. We have proposed a ranked list of 43 everyday objects for the evaluation of assistive mobile manipulation systems operating in domestic settings. We have used methods of user-centric design to create and validate this list with a

group of severely motor impaired individuals, consisting of ALS patients. By developing benchmarks tailored to specific application domains and user populations, researchers have the opportunity to ground their research and answer the otherwise subjective question: *What is important?*

CHAPTER V

HUMAN EVALUATION PHASE I

This chapter describes the first evaluation study with eight ALS patients, which focused on the task of object fetching. Based on interviews of patients with amyotrophic lateral sclerosis (ALS), we developed and tested three distinct control interfaces that enable a user to provide a 3D location to the robot and thereby select an object to be manipulated: an ear-mounted laser pointer, a hand-held laser pointer, and a touch screen interface. Within this chapter, we present the results from a user evaluation study comparing these three user interfaces with a total of 134 trials, involving eight patients with varying levels of impairment recruited from the Emory ALS Clinic. During this study, participants used the three control interfaces to select everyday objects to be approached, grasped, and lifted off of the ground by the robot. The three interfaces enabled motor impaired users to command a robot to pick up an object with a 94.8% success rate overall after less than 10 minutes of learning to use each interface. On average, users selected objects 69% more quickly with the laser pointer interfaces than with the touch screen interface. We also found substantial variation in user preference. With respect to the Revised ALS Functional Rating Scale (ALSFRS-R), users with greater upper-limb mobility tended to prefer the hand-held laser pointer, while those with less upper-limb mobility tended to prefer the ear-mounted laser pointer. Despite the extra efficiency of the laser pointer interfaces, three patients preferred the touch screen interface, which has the unique potential for manipulating remote objects out of the user's line of sight. In summary, the results of this study indicate that robots have the potential to improve an individuals quality of life through assistance

with an important, everyday task – object retrieval. Additionally, this study illustrates that the communication of 3D locations during human-robot interaction can serve as a powerful abstraction barrier that supports distinct interfaces to assistive robots while using identical, underlying robotic functionality. The results shows that 1) robots can assist those with motor impairments by helping with object retrieval; 2) this can be achieved through the relatively simple human-robot interaction method of the user conveying 3D coordinate information to the robot (and vice versa, depending on the method of communication and whether the object is remotely located, visible to the user or not; and 3) that relatively simple and easy to implement control devices can be created to suit different users capabilities, allowing them to control the robot for this task.

5.1 *Introduction*

For many forms of assistive object manipulation, such as object fetching, users will want to unambiguously select an object. In a previous study, we have shown that providing a 3D location to the robot, specified with respect to the robot’s body, is sufficient to command the robot to perform a variety of tasks, such as moving to a location, picking up an object, delivering an object to a person, and placing an object on a tables [49]. We have also shown that an off-the-shelf hand-held laser pointer can be used by able-bodied lab members (robotics experts) to select a 3D location and reliably command the robot. In this chapter, I present two new interfaces that we have developed based on our interviews with ALS patients, which make use of an ear-mounted laser pointer and a touch screen computing device. I also evaluate and compare the efficacy of all three interfaces through a study involving eight patients recruited from the Emory ALS Clinic. In this first study with prospective users, seven ALS patients and a patient with primary lateral sclerosis (PLS) participated in a lab-based experiment with these three user interfaces: an ear-mounted laser pointer (EL),

a touch screen graphical user interface (TS), and a hand-held laser pointer (HL). The participants were asked to direct the robot to pick up an object from the floor by selecting it while using the given control interface, which involves illuminating the object with a green laser or touching the image of the object on the touch screen.

5.2 *Motivation*

One of the most significant problems that individuals with motor impairments experience is a loss of independence due to difficulty in performing daily tasks such as washing, eating, opening doors, and picking up objects. Individuals with motor impairments have consistently cited object retrieval from the floor and shelves as an important area for robotic help [82]. Assistance provided by human caregivers is limited by availability and expense, both in care facilities and in the home. Family members are currently a primary source of assistance for those with limited motor skills, but family assistance requires that they be present for prolonged periods of time, limiting their freedom and creating potential challenges to familial and spousal relationships. Due to the expense and difficulty of finding human assistance, as well as issues of independence and privacy, helper animals have been trained to aid individuals. For example, helper monkeys have been trained and then placed with motor impaired individuals through organizations such as Helping Hands [33]. Monkeys have high dexterity and are capable of performing various manipulation tasks that are helpful to humans with motor impairments. For example, a monkey can pick up and retrieve an object when directed by a quadriplegic with a mouth-operated laser pointer. This method of interaction has served as an inspiration for our laser pointer interface. Although highly trained animals can provide effective assistance, they come with a host of other complications, including high costs (\$17000-\$35000), extensive training (2-5 years), reliability issues, and their own need for care.

5.3 *Related works*

The objective of this chapter is to evaluate Human-Robot Interaction (HRI). Compared to traditional human-computer interaction (HCI), HRI is still a relatively young field of study. Yanco, Drury, and colleagues [104] have evaluated different implementations of HRI in a search and rescue mission contest. The robots usually performed in an autonomous way while the controllers remotely monitored their activities and gave high-level commands. This study focused on evaluating the graphical user interface (GUI) of the remote control devices, so HRI evaluation in this study was similar to evaluations in traditional HCI studies, in which GUI issues are investigated. Huttenrauch and Eklundh reported a study involving the development of a service robot designed to help elderly people [38]. Unlike the robot used in our studies (El-E), this robot only transports objects that are placed onto it. It does not have manipulation capabilities. In contrast to our work, which focuses on controlled lab-based experiments, this study involved long-term field testing of the developed prototype with human users. After a training period, the robot was put into the user's home environment without direct observation, although log files were collected. Our controlled study has enabled us to quantitatively compare the performance of three distinct user interfaces.

A recent study designed and evaluated different robot-user interfaces to meet the needs of people with various impairments, including cognitive impairments, comparing a joystick and a touch screen interface to control a semi-autonomous wheelchair-mounted robotic arm [89]. In contrast to this work, our study focuses on motor impairments, uses an autonomous mobile robot manipulator, evaluates whether the robot successfully performs a relevant manipulation task (i.e., picking up an object) when commanded by a user, and tests two novel laser-pointer interfaces in addition to a touch screen user interface.

5.3.1 Implementation

During the series of human studies conducted, our lab continuously improved and modified implementation of the ear-mounted laser pointer-E. In this section, we describe the status of implementation at the time period of the first human evaluation. The implementation used in the second human evaluation will be described in the Implementation section of the next chapter. Figure 43 shows the implementation of the assistive robot, El-E, at the time of the evaluation study. A vertical lift is used for vertical movement of a carriage holding a 5 DOF (degree of freedom) manipulator, a 1 DOF two finger gripper, a laser range finder, and a camera. A mobile base, with two driven wheels and a passive caster, holds other robot components. On the top of the vertical lift, the head portion of the robot works as a visual system for the robot, containing two different types of camera systems. The hyperbolic mirror near the top of Figure 43 and a monochrome camera constitute an omnidirectional camera system. Due to the shape of the mirror, the camera has a comprehensive view of the local surroundings horizontally 240 degrees with a small blind area blocked by the linear actuator and vertically from the floor to the ceiling. This enables El-E to monitor most of a room. The robot uses a stereo camera system, mounted on a pan and tilt unit, to obtain detailed color images of the room and to compute estimates of 3D locations. The two-finger gripper is equipped with force-torque sensors for grasping objects. A laser range finder with a 4 meter range is mounted on the carriage, which allows the laser range finder to scan across the surfaces of planes of various heights, such as floors and tables.

During this study, when given a 3D location by the user, the robot moves towards the location and uses its laser range finder to look for an object close to the indicated 3D location. If it finds an object that is sufficiently close to the 3D location, it moves to the object, moves its gripper over the object, uses a camera in its hand to visually segment the object, aligns the gripper at an appropriate angle, and then moves its

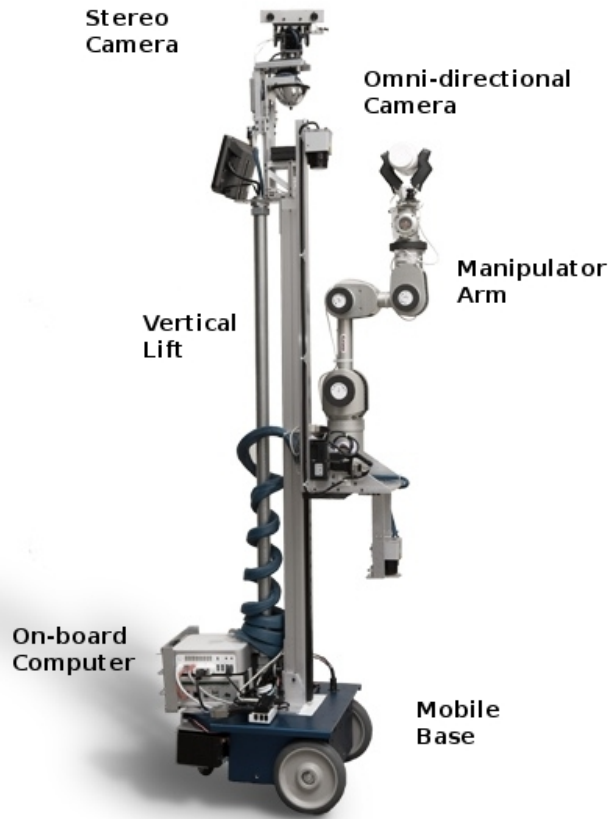


Figure 43: El-E and its components

gripper down to the object while monitoring the force-torque sensors in its gripper. Once it makes physical contact with the object, it stops the gripper's descent and begins closing the gripper. In the event that it does not successfully grasp the object the first time, it will try again, up to four times.

The mobile base is built from a commercially available mobile robot. It transports the other hardware components of the robot and is controlled by an on-board computer with a wireless link. An on-board Mac Mini computer with a Linux operating system performs all the computation required for the robot's autonomous operation.

5.3.2 Abstraction layer of 3D locations

A key aspect of this study is that although each of the three interfaces provides a 3D location to the robot using a distinct method, the robot operates in exactly the same way once the 3D location has been provided. The 3D location serves as an abstraction barrier or communication protocol between various human interfaces and the robot’s autonomous capabilities, see Figure 44. As such, when designing a new interface, one only needs to ensure that the interface will provide the robot with a 3D location with respect to the robot’s body with sufficiently low spatial error. This separation of concerns can simplify the development of new interfaces by enabling the interface designer to focus on the interface as opposed to the robot. As our study shows, this can be especially important for meeting the varied needs of the motor impaired, since a single user interface is unlikely to be preferred by or meet the limited physical capabilities of all. Our study also validates that this abstraction barrier works, since the robot runs the exact same code once a 3D location has been provided by one of the three interfaces. It is worth noting that this architecture is similar to the point-and-click model of interaction used with personal computers (PCs). Most 2D windowing systems found on modern PCs are agnostic about the specific interface used to provide a 2D location. This has facilitated the development of a diverse array of interfaces for PCs, including track balls, optical mice, and eye tracking devices, and has undoubtedly helped to make PCs more accessible to all users, especially those with varying sensory, cognitive, and motor capabilities. We expect a similar architecture to have a comparable beneficial impact on robotics.

5.3.3 User interfaces

The hand-held laser pointer is a standard off-the-shelf laser pointer with a green laser that is commonly used for slide presentations. Although a hand-held laser pointer provides an easy and intuitive method to unambiguously point to a real world object

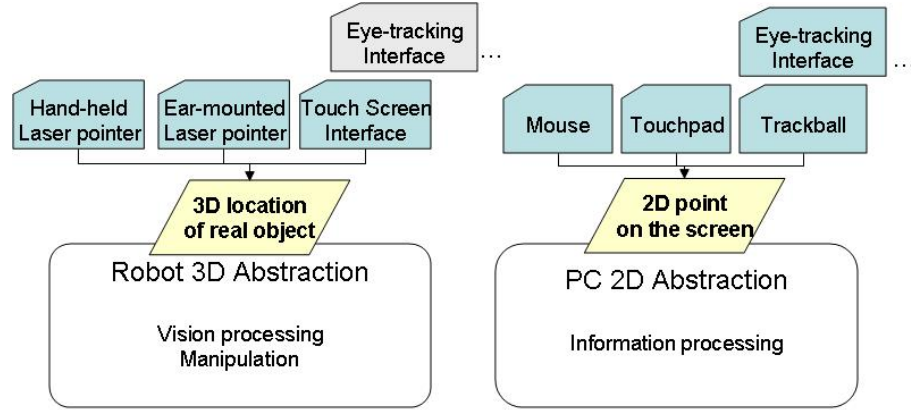


Figure 44: 3D and 2D abstraction layers



Figure 45: A hand-held laser pointer being held by a participant

within the three dimensional world, handling it requires strength and dexterity of the upper-limbs. As shown in Figure 45, a participant with limited hand dexterity uses both hands to point the pointer and press its button.

The hand-held and ear-mounted laser pointer interfaces use a point-and-click style of interaction analogous to the interaction style used in common graphical user interfaces. This interface enables the user to point to an object in the three dimensional world with a conventional laser pointer, similar to the use of a mouse pointer on the two dimensional screen of a PC interface.

When a user turns on the laser pointer and orients it toward a specific object,



Figure 46: Ear-mounted laser pointer and a wired button

the laser light emitted from the laser pointer is reflected off the surface of the object. When the user points to an object and illuminates it with the laser pointer for a few seconds, it is recognized as a 'click' command. The cameras on the robot produce images of the scene. Because the laser light has a well-defined frequency, a characteristic shape, and predictable motion, the robot can readily detect the illuminated location. To enhance the detection of the laser spot with the omnidirectional camera and to increase the sensitivity, the robot uses a narrow-band green filter matched to the specific frequency range of the laser pointer. After detecting the spot, the robot looks at it and estimates its 3D location using the stereo camera.

We designed the ear-mounted laser pointer to appeal to users with limited upper-limb mobility. We connected a green laser diode, which emits light, to a control unit consisting of batteries and a push button, as shown in Figure 46. Separating the battery and button from the laser diode helps reduce the weight of the ear-mounted component, which is based on an off-the-shelf ear-hook style Bluetooth headset shown in Figure 47. We expect the ear-hook design to be less obtrusive than alternatives, such as a hat, a hair band, or a headphone.



Figure 47: Ear-mounted laser pointer worn by a participant



Figure 48: Touch Screen Interface



Figure 49: The touch screen interface being used by a participant

Additionally, we implemented the touch screen GUI on a computer separate from the robot and located in close proximity to the user as shown in Figure 49. The GUI has a large area in its center that displays images from the robot’s right stereo camera. On the left and right side of the image, we included large arrow buttons to enable the user to look around the room by panning and tilting the stereo camera as shown in Figure 48. When using the interface, the user first orients the view of the camera toward the object of interest by pressing the arrows. Next, the user selects the object by touching the object in the image display area. The robot uses this selection to compute a 3D estimate of the object’s location. The 3D estimate is then used by the robot in the same manner as the 3D estimate from the laser pointer interfaces. During study trials, the participants put the touch screen display on their laps and used the interface with both hands interface, as shown in Figure 49.

5.3.4 Participants

Eight participants took part in this study. The demographic profile of this participant sample is resented in Table 20. Seven participants were ALS patients, while the remaining patient was diagnosed with primary lateral sclerosis (PLS). PLS is clinically different than ALS, but also causes severe motor impairments and can be categorized

Table 20: Demographic information

Variables	Values
Gender	Male (6), Female (2)
Ethnicity	White (6), African American (2)
Age	35 - 67 (average 53.13) years
Diagnosis	25.16 (average for all) 15 months ago (for 7 ALS patients)

within the same family as ALS. Five of the seven ALS patients previously participated in the needs assessment study. We recruited participants by meeting them in the Emory ALS clinic and through telephone calls. Participants had considerable variety in the extent of their impairment, ranging from slight difficulty with walking to serious impairment in limb mobility (for example, only possessing slight motion of a single hand). Participants volunteered to visit our laboratory to take part in the user evaluation study.

5.3.5 Experimental setting

Figure 50 shows an overview of the experimental setting. During the experimental trials, patients sat on a wheelchair or a common desk chair beside the robot’s initial position. We chose this relative positioning of the robot and the user to emulate the use of a service dog. In this sense, one can think of the robot as a companion robot that stays by the side of the user. For this study, all objects were placed in one of two positions, which were marked by tape on the lab floor. From the user’s perspective position A is on the left and position B is on the right. The two positions were selected to represent different directions and distances from the robot as listed in Table 21. When placed in these two positions the objects were in plain sight of both the robot and the participant. 3D estimation of the point detected by the robot was compared with the object location to calculate the 3D distance between the objects’ actual locations and detected points.

To validate the performance of the robot with objects with different shapes,



Figure 50: Overview of experimental setting

Table 21: Direction and distances of object locations

Location	X offset	Y offset	Distance
A	1.964	0.195	1.975
B	1.54	-0.57	1.642

weight, and colors, we used three everyday health-related objects for the experiment; 1) a cordless phone, 2) a paper medicine box, and 3) a plastic medicine bottle, as shown in 51.

5.3.6 Procedures

For this study we used a within-subjects design, in which all users conducted tasks with all conditions. The order of two factors - interface type and object type - was randomized to minimize order effect and to ensure counterbalancing. We used the following procedure to conduct the experiment with each participant:

1. Participants read and signed consent forms and responded to surveys on computer experiences and upper-limb and neck mobility.



Figure 51: Objects; a cordless phone, a paper medicine box, and a plastic medicine bottle

2. For the first interface type, randomly chosen among ear-mounted laser pointer, touch screen, and hand-held laser pointer, the participant learned to use the interface and practiced until he/she indicated comfort and confidence.
3. For each of the three object types (in randomized order), the participant conducted two trials, one for each position (A&B) resulting in a total of 6 trials for each interface type.
4. We conducted a satisfaction survey to record the user's experience with the control interface.
5. Steps 2 through 4 were repeated for the other two interface types.
6. The participants answered final post-task interview questions.

The total time for each experiment was limited to 2 hours to prevent fatigue and lasted an average of approximately 1.5 hours. Separate from the experiment, an assessment of ALSFRS-R was conducted by clinical personnel in the Emory ALS Center to determine the extent of ALS disease progress.

5.3.7 Quantitative Performance Measures

Time to completion is a primary measure of assessing the performance of human-machine systems [4]. For the purposes of this study, we divided the total time to completion into;

1. Selection time: The time elapsed between when the user started to use the interface by notifying the experimenter to when the robot detected the target's 3D position.
2. Movement time: The time between the selection to when the robot approached the target and fixed its position.
3. Grasping time: The time from when the robot finished approaching to when the robot finished the task.

Out of these three task decompositions, we expected the selection time to be the most relevant measure to detect differences among the three different user interfaces, as the robots operation was consistent from the point of receiving the 3D location information from the user. We expected movement time to be highly correlated with the position of the objects and the grasping time to be dependent on the object types. The Euclidian distance between the object's actual 3D location and the 3D location used by the robot serves as a measure of accuracy for pointing tasks with the three interfaces. We recorded the 3D location in log files and calculated the distance as a measure of pointing error in the analysis.

5.3.8 Qualitative Measures

Human-computer interaction researchers often conduct satisfaction questionnaires after experimental trials to measure the user's satisfaction with a computer interface and has proven this method to be effective in long term user studies [25]. Because the purpose of this study is to evaluate the user interface for directing the robot,

we used an existing satisfaction questionnaire developed for evaluating computer systems [59] to derive a questionnaire with 8 items. We asked the following questions to qualitatively measure participant satisfaction:

1. I could effectively use the system to accomplish the given tasks.
2. I am satisfied with the time between when I gave command and when the robot detected the object.
3. I am satisfied with the total time between when I gave command and when the robot finally picked up the object.
4. It was easy to find an object with the interface
5. It was easy to point an object with the interface.
6. It was easy to learn to use the system.
7. It was not physically burdensome to use the system.
8. Overall, I was satisfied to use the system.

The participants were asked to answer on a 7 point Likert scale from strongly disagree (-3) to strongly agree (3)

5.4 Results

Across the total of 134 trials, participants commanded the robot to pick up an object with a 94.8% overall success rate with the three interface types. It took less than 10 minutes of learning to use each interface for all participants. Users could select objects 69% more quickly with the laser pointer interfaces than with the touch screen interface. We also found substantial variation in user preference. Users with greater mobility in arms and hands tended to prefer the hand-held laser pointer, while those with more difficulty in upper-limb movement tended to prefer the ear-mounted laser

Table 22: Averages (standard deviation) of quantitative measures by interface type (in seconds)

Interface	Selection	Move	Grasp	Total	Pointing error
Ear-mounted laser pointer	4.80 (3.80)	24.51 (4.11)	148.01 (64.20)	176.76 (65.89)	0.25 (0.27)
Touch screen GUI	17.16 (29.31)	28.94 (31.45)	144.72 (50.12)	187.46 (56.71)	0.30 (0.85)
Hand-held laser pointer	5.27 (3.59)	24.46 (4.22)	134.79 (32.87)	159.55 (43.52)	0.22 (0.27)

pointer. We also found that three patients preferred to use the touch screen interface, despite it taking a longer time to complete the task. These results indicate that assistive robots can serve as a proxy for object retrieval tasks and also demonstrates that the communication of 3D locations from a user to the assistive robot can serve as an effective abstraction barrier that enables the use of different interfaces to control the robot, while maintaining identical robotic functionalities.

5.4.1 Quantitative Measures

We conducted a total of 134 experimental trials. Six participants performed eighteen trials, using the three interfaces described above. One participant was only able to perform twelve trials with the ear-mounted laser pointer and the touch screen GUI due to weak upper-limb mobility. The remaining participant performed 12 trials with the touch screen GUI and the ear-mounted laser pointer but only 2 trials for the hand-held laser pointer. In 127 out of 134 trials (94.8%), the robot successfully picked up the object. The seven failed trials involved all three interfaces; 2 for the ear-mounted laser pointer, 3 for the touch screen GUI, and 2 for the hand-held laser pointer. It should also be noted that six of the seven failures occurred during the trials of one particular participant. In Table 22, we list the averages and standard deviations of quantitative performance measures based on the interface type.

Table 23: ANOVA table of the selection time

	Df	Mean Square	F	Sig.
Between Groups	2.00	2138.32	7.023	0.001
Within Groups	125.00	304.49		
Total	127.00			

As anticipated, the most apparent difference between the performance of the interfaces was found in the selection time measure. The touch screen GUI interface took considerably longer to select objects compared to the ear-mounted laser pointer and the hand-held laser pointer interfaces. Based on the results from the analysis of variance (ANOVA) test, the only statistically significant difference was found in the selection time (see Table 23). After the one-way ANOVA, Tukey’s post-hoc tests were conducted to find the loci of the significant differences between selection times of the interface types. The results showed that there was a significant difference between selection times of the ear-mounted laser pointer and the touch screen GUI, and between selection times of the hand-held laser pointer and the touch screen GUI. On average, the laser pointer interfaces (the hand-held laser pointer and the ear-mounted laser pointer) were 69% faster (see the first column of Table 3) than the touch screen interface (the touch screen GUI). Improvements to the design of the touch screen interface could potentially reduce this selection time. However, we believe a difference between selection time for the laser pointers and the touch screen would persist regardless of any design and performance improvements to the touch screen control interface. The touch screen GUI interface requires that the user first make the desired object visible on the touch screen at a high enough resolution to touch it. For our current implementation, this requires the user to move the robot’s stereo camera around with arrow buttons until the object is in view. During this operation, most users first locate the object using his or her own eyes and then moved the robot’s cameras accordingly. Even with changes to this process, such as integrating an omnidirectional camera view with the touch screen, we expect humans to find a nearby

object more efficiently by looking for it in the real world. Moreover, if the person is already involved in a real-world task involving nearby objects, using the touch screen could require the user to momentarily shift perspectives, which could reduce efficiency further. As we have previously mentioned, these advantages of the laser pointer interfaces disappear if the object is out of the line-of-sight of the user and the robot, in which case the laser pointer interfaces would be completely ineffective without altering the location of the user. In this case, a touch screen does have distinct advantages of being able to handle remotely located (e.g., in another room or overhead or otherwise not readily visible) objects. As expected, the movement and grasp time did not vary significantly with the interface types. As a measure of the error in pointing, we calculated the distance between the object’s location and the selected location. The average pointing error with the hand-held laser pointer and the ear-mounted laser pointer was smaller than with the touch screen GUI, although the difference was not statistically significant. The variance of the pointing error was much greater with the touch screen GUI.

5.4.2 Subjective measures

The total scores for the satisfaction survey for each interface were 50.86 for the ear-mounted laser pointer, 49.71 for the touch screen GUI, 47 for the hand-held laser pointer with a maximum value of 56. Across the user population, there were no apparent differences between the average satisfactions for the interface types, with all being well accepted by the participants. In the final interviews, participants were asked which laser pointer was more comfortable and which interface, including the touch screen GUI, they preferred to use. The laser pointer interface that users described as more comfortable was highly related to their upper-limb mobility. Among the 13 items of ALSFRS-R scores, Handwriting, Dressing and Hygiene are more related to upper-limb ability than other items. The total ALSFRS-R score includes

Table 24: Interface preferences and ALSFRS-R scores

	P1	P2	P3	P4	P5	P6	P7	P8
Comfortable (HL vs. the EL)	HL	EL	EL	HL	EL	EL	HL	HL
Prefer to use (HL vs. EL vs. TS)	HL	EL	EL	HL	TS	TS	HL	TS
Handwriting	3	0	0	4	2	1	3	3
Dressing and Hygiene	2	0	0	2	1	1	3	1
Total ALSFRS-R	37	18	27	30	25	19	39	16

other general health and respiratory assessment attributes which are important but are not directly related to the strength and dexterity of the hands and arms. As shown in Table 24, all participants with higher Handwriting scores (e.g., greater than or equal to three) answered that the hand-held laser pointer was more comfortable than the ear-mounted laser pointer. Combined with Dressing and Hygiene, it is clear that the ear-mounted laser pointer is more comfortable to use by participants with limited upper-limb mobility. However, three participants preferred to use the touch screen GUI regardless of which laser pointer interface was more comfortable, despite the fact that the touch screen GUI required longer selection times than the laser pointers.

In the post-task interviews, we learned the reasons why participants preferred one specific interface to the others. The hand-held laser pointer was preferred because it was easier and quicker, at least for those participants with sufficient upper-limb ability. The ear-mounted laser pointer was preferred because it made a participant feel more in control and did not require upper-limb strength and/or fine motor skills. One participant felt that the touch screen GUI was more functional and more accurate. Participant feedback also indicated that each interface design had some room for improvement. Participants felt that the hand-held laser pointer was heavy and the button was difficult to press and hold for some participants. One participant noted that the button of the ear-mounted laser pointer was difficult to press and a larger button would be preferred. Participants suggested using a trackball or joystick to control the touch screen GUI or rearranging the buttons to make it more easily

controllable during one-handed use. These suggestions will be valuable in improving the user interfaces. Overall, the ear-mounted laser pointer had wider applicability because all participants could effectively move their head to use it while many participants experienced difficulty in holding the hand-held laser pointer. One participant used both hands and both legs to support the hand-held laser pointer during the experiment. Even though use of the hand-held laser pointer resulted in slightly longer selection time, some participants preferred the hand-held laser pointer to the ear-mounted laser pointer.

5.5 Conclusion

This work represents an initial study in an important area of assistive technology. Future research could build on this work in a number of ways, including the use of larger participant populations, more diverse, natural environments with clutter present, and retrieval of greater numbers of objects with more varied placement. In our interviews with ALS patients in the needs assessment study conducted prior to the present study, participants stated that they frequently dropped objects and had considerable difficulty in retrieving them without help from their caregivers. Our experimental results demonstrate El-E's usefulness for acquiring objects to meet these stated needs. All three interfaces proved effective in the object manipulation task with an overall success rate of 94.8%. Although no participant had previous experiences with controlling robots like El-E, all of the participants were able to use the robot with any of the three interfaces in less than 10 minutes, which implies that the robot was easy to use for the prospective users. Although we found a significant difference in the selection time measurement between the laser pointers and the touch screen interface, all three interfaces were well accepted by the prospective users. Through the satisfaction questionnaire and post-task interviews, participants consistently expressed satisfaction in their experiences with the robot using all three interfaces. Specifically, the

ear-mounted laser pointer was identified as the more comfortable laser pointer interface for those patients with limited strength and dexterity of upper-limbs. Among the eight participants, the ear-mounted laser pointer, the hand-held laser pointer, and the touch screen GUI were preferred by two, three, and three participants, respectively. This suggests that different individuals will benefit from the design of different user interfaces that can be used to control assistive robots; with the nature of the best user interface dependent on the nature of the individuals impairment. As one participant mentioned, a “one-size-fits-all solution does not work.”

CHAPTER VI

HUMAN EVALUATION PHASE II

The ability to deliver an object to a user represents a generally useful function for service robots. Within this chapter, we look at this capability within the context of assistive object retrieval for motor-impaired users. First a behavior-based system, the ear-mounted laser pointer-E, that enables our mobile robot to autonomously deliver an object to a motor-impaired user is described. We then present our evaluation of this system with 8 motor-impaired patients from the Emory ALS Center. As part of this study, we compared handing the object to the user (direct delivery) with placing the object on a nearby table (indirect delivery). The delivery of a cordless phone, a medicine bottle, and a TV remote was tested, which were ranked as three of the top four most important objects for robotic delivery by ALS patients in a previous study. Overall, the robot successfully delivered these objects in 126 out of 144 trials (88%) with a success rate of 98% for indirect delivery and 78% for direct delivery. In an accompanying survey, participants showed high satisfaction with the robot, with 4 people preferring direct delivery and 4 people preferring indirect delivery. The results indicate that indirect delivery to a surface can be a robust and reliable delivery method with high user satisfaction. However, for users who prefer and/or need direct object delivery, the improvement of this process will require methods that can handle the diverse postures and body types that exist amongst individuals.

6.1 *Introduction*

Service robots that reliably deliver objects to users could be valuable for a variety of applications. For example, a robot that assists a mechanic could deliver a tool, while a robot that prepares food could deliver a meal. Within this study, we look at how

an assistive robot can deliver an object to an individual with motor impairment.

As described in the previous chapter, I performed a human evaluation study with 8 patients in which the users commanded EL-E to approach and pick up an object using three different user interfaces. In order to successfully complete the retrieval of an object, the robot must deliver the object to the user after picking it up. Within this study, we report on our most recent study, in which 8 patients commanded the robot to either hand them an object directly or place the object on a nearby table. Six of these patients had not previously interacted with the robot, while one had previously worked with the robot informally, and another had participated in our prior study.

For this work, we assume that the user wishes to gain direct control of the object that the robot is carrying without the object falling onto the floor or otherwise moving unfavorably. We further assume that at the end of a successful trial the robot must not be making contact with the object, and the user must be holding the object. For some severely motor-impaired users, it may be more appropriate for the robot to continue to hold the object so that the user can control the object through the robot. However, we do not investigate this possibility here.

Given these assumptions, the robot must somehow transfer control of the object to the user in a controlled and stable manner (e.g., not throwing the object). Humans frequently achieve this feat without difficulty. Waiters, in particular, serve as an informative example of successful strategies for delivering an object. Waiters typically hand an object directly to a patron, place the object on the table next to the patron, or present a tray from which the patron can grasp the object. Within this study, we compare two strategies for robotic object delivery: handing the object to the user and placing the object on a table next to the user. Our results show that these two methods have distinct implications.



Figure 52: El-E handing a cordless phone to an ALS patient. Photos used with patient permission and IRB approval.

6.2 *Related works*

There is a long history of research focusing on the development of robots designed to assist people with motor impairments. For instance, The Assistive Robotic Manipulator, known as MANUS, is a commercially-available, wheelchair-mounted robotic arm (WMRA) [53]. MANUS can help individuals with various tasks including object fetching and retrieval by controlling the arm by joystick and keypad. Since the direct teleoperation of this kind of robotic device is often difficult, researchers have been developing autonomous capabilities for these robots, such as [30, 89]. The FRIEND II robot, another WMRA, includes an intelligent tray that serves as an object delivery location. In general, WMRAs have the capability to place an object within the reach of the user without much difficulty due to the fixed configuration between the arm and the user [60]. However, WMRAs require that the user drive the wheelchair system to the desired object in order for the arm to grasp it. Thus, one advantage of mobile manipulator platforms that are decoupled from the user's chair is the elimination of the need for the user to be at the site of object retrieval.

Taking a more fundamental approach, researchers have attempted to characterize the mechanics involved when objects are handed between people or between a person and a robot. Shibata and colleagues [79] studied the motions involved when two humans hand each other an object to determine the trajectories and velocities of their hands during the task. Other researchers have used these human hand trajectories to simulate a human delivering an object to a robot using potential fields [42]. Another simulation study incorporated a controller to allow a robot to receive an object from a human while safely taking into account unexpected human movements [2]. Beyond simulation, a recent study used a 2D planar robot to assess human preference for delivery velocity and position during a human-robot object hand-over task [41]. Analysis has also been done on the grip forces or torques used when passing an object [62, 66].

Several mobile platforms have also been developed to deliver objects to able-bodied people. For instance, planning algorithms have been developed to find safe trajectories for handing objects as seen with Jido and Care-O-bot II [81, 80, 31]. A behavior-based approach that enables a robot on a fixed platform to hand objects to able-bodied people has been shown to allow intuitive human-robot interactions [22].

Autonomous mobile robots have also been developed to deliver objects to help elderly and motor impaired individuals perform everyday tasks. For instance, Mobile Assistant Robot for You (MARY) and Care-O-bot 3 are mobile manipulators that can fetch and deliver objects by placing them on a tray, which is attached to the robot’s front panel, before moving closer to the receiver [85, 26]. Similarly, CERO delivers objects that have been placed on top of it to motor-impaired individuals [38]. However, none of these autonomous delivery systems has been tested directly with the elderly or the motor-impaired populations whom their technologies aim to serve. The robot SAM has been tested with motor-impaired users in terms of object grasping, but studies of its delivery capabilities do not appear to have been performed [74].

Compared to above existing studies of robotic object delivery, our human study of object delivery presented in this chapter has two distinct contributions. First, we developed two representative methods of delivery and compared them through human studies. Existing studies relied on a specific delivery method of handing-over, or placing on a surface such as tray without justification on why they chose the specific method of delivery. As we found in our evaluation study, direct delivery to the hand and indirect delivery on a surface provide very different experiences to users with motor impairments. Secondly, we evaluated the implemented delivery methods with active participation of target population having severe motor impairments. Because ALS patients have less upper limb mobility and dexterity, successful implementation of delivery to able bodied users do not guarantee that the solution will also work for the patients. Additionally, the fact that most users use the robot while sitting on

a wheelchair presents another technical challenges for the robot to find appropriate destination of delivery and to avoid collision into the users body.

In designing the human evaluation study presented in this study, we considered the prior work on user preferences during a mobile robot delivery task. Users tended to dislike when the robot approached them from the front, and preferred an approach either their left or right side [18, 98]. We reflect these findings in the Experimental Setup.

6.3 *Implementation*

This section describes the robot, the ear-mounted laser pointer-E, that was used in the second human evaluation. We then explain the safety mechanisms that we have implemented on the robot in Section 6.3.2 and the behaviors that implement the direct and indirect delivery in Section 6.3.3.

6.3.1 The robot

The ear-mounted laser pointer-E robot is a statically stable mobile manipulator (shown in Figure 53) that consists of a 5-DoF Neuronics Katana 6M manipulator, an ERRATIC mobile base by Videre Design, and a 1-DoF linear actuator that can lift the manipulator and various sensors from ground level to 90cm above the ground [69]. The robot also uses the Festival Speech Synthesis System to give users feedback by speaking fixed sentences in English. For example, the robot asks the user to give it a laser command or to grasp an object from its gripper.

The ERRATIC platform has differential drive steering with two powered wheels and one passive caster at the back. A Mac Mini computer running Ubuntu GNU/Linux performs all computation on-board. We have written most of our software in Python with occasional C++ utilizing a variety of open source packages including SciPy, Player/Stage, OpenCV, and ROS (Robot Operating System).

For this work, the ear-mounted laser pointer-E robot uses three distinct types

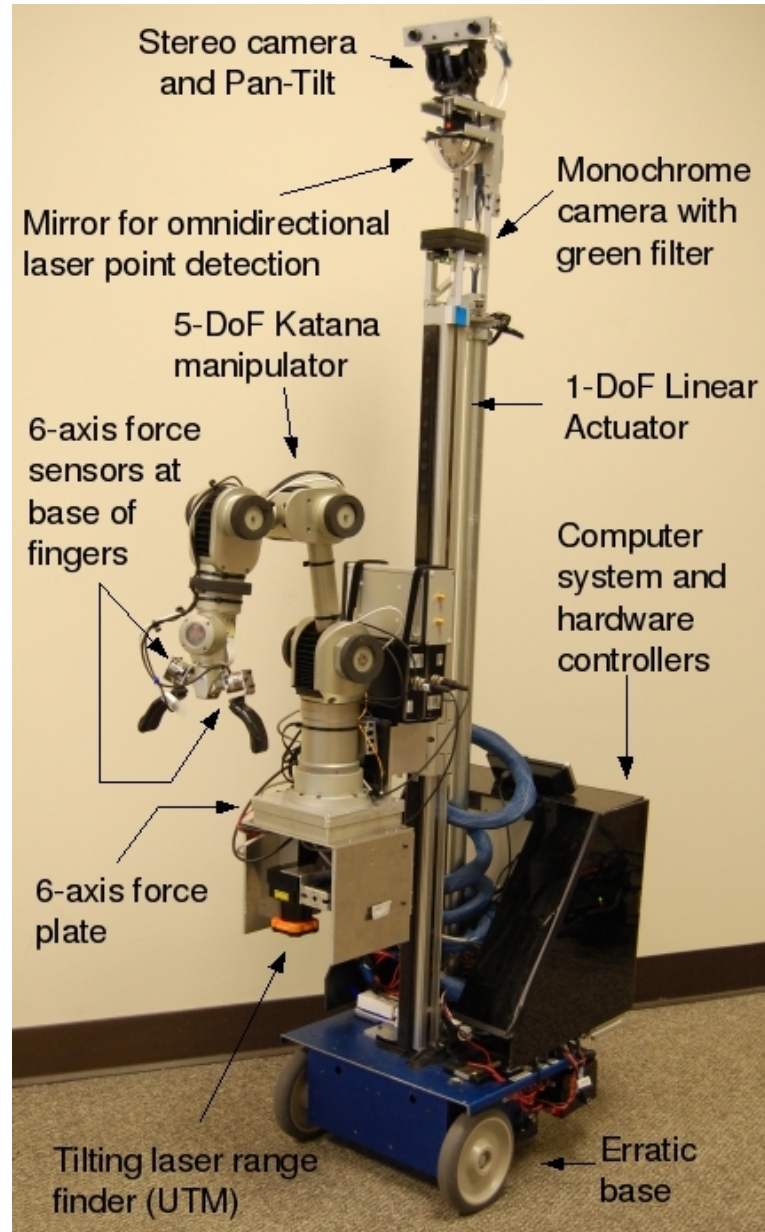


Figure 53: The mobile manipulator, the ear-mounted laser pointer-E, used in this chapter.

of sensors. First, the robot uses a laser pointer interface that consists of an omnidirectional camera with a narrow-band green filter that is designed to detect a green laser spot and a pan/tilt stereo camera that estimates its 3D location [49].

Second, the robot uses a laser range finder (Hokuyo UTM-30LX) mounted on a servo motor (Robotis Dynamixel RX-28) at the bottom of the aluminum carriage attached to the linear actuator. The servo motor tilts the laser range finder about the horizontal axis. The robot uses this tilting laser range finder to obtain 3D point clouds of the environment.

Third, the robot senses forces and torques using force-sensing fingers and a 6-axis force plate. We have replaced the Katana Sensor Fingers with our own custom fingers. Each finger is a curved strip of aluminum covered with elastic foam for passive compliance and is connected to the motor via a 6-axis force/torque sensor (ATI Nano25 from ATI Industrial Automation). This enables the robot to measure the resultant forces and torques being applied on each finger independently. In addition to the force sensing fingers, we have mounted the Katana on a 6-axis force plate (HE6X6 from AMTI). The force plate allows the robot to sense forces applied to any point on the Katana arm.

6.3.2 Safety mechanisms

We describe three methods that we use to help ensure safe operation of the robot. First, we use the laser range finder as a safety screen to detect obstacles and prevent collisions while the robot navigates. Second, we use force sensing to detect collisions between the manipulator and objects in the environment, including (most importantly) the users.

6.3.2.1 Obstacle detection using a safety screen

When the ear-mounted laser pointer-E robot moves, it lifts the tilting laser range finder to a height of approximately 90cm off of the ground and tilts it down. In this

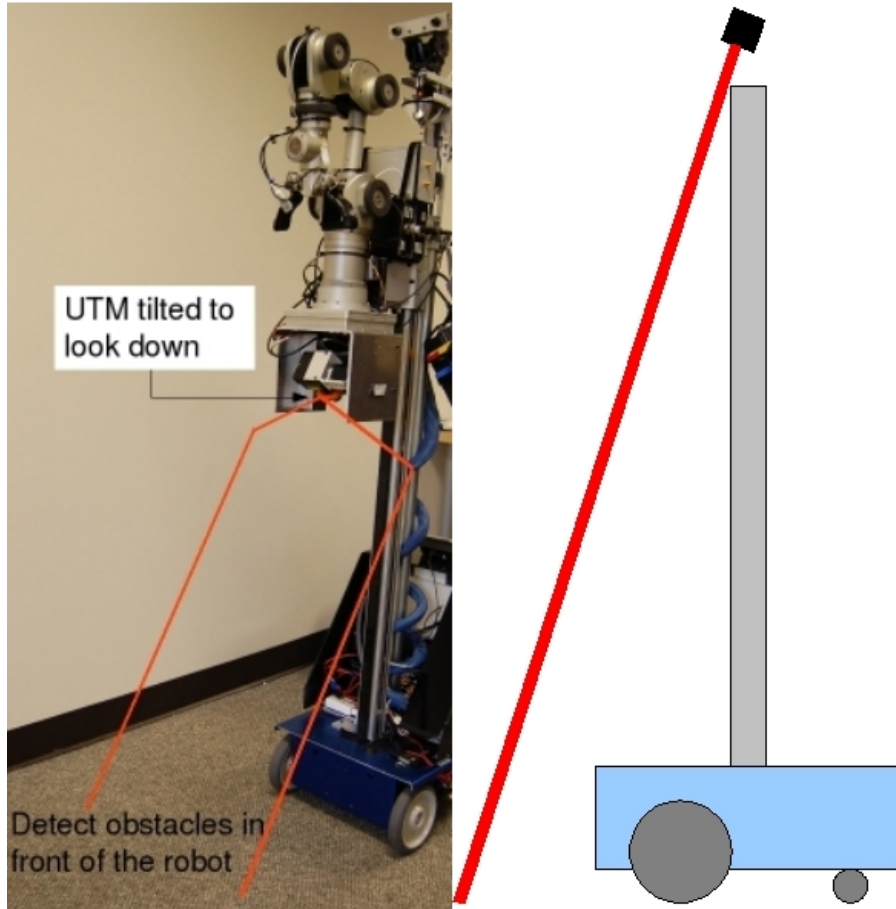


Figure 54: Left: Our current implementation using a laser range finder for real-time obstacle detection in the form of a safety screen. **Right:** A sketch of our plans for a new actuated laser range finder that can pan and tilt in order to improve the coverage of the safety screen.

way the robot can detect obstacles, such as table tops and people, that get close to its body. This helps to ensure that it stops before colliding with anything. We refer to this as a “safety screen”. For future versions of the robot, we plan to place an actuated laser range finder that can pan and tilt at its top. This will enable the robot to monitor for potential collisions over its entire body, regardless of the direction in which it is moving (see Figure 54). Currently, the robot lifts its carriage to approximate this sensor configuration.

6.3.2.2 Collision detection using force sensing

When the robot moves the manipulator to hand the object to a user or to place the object on a table, it monitors the force plate and the force sensing fingers and freezes the manipulator if it detects a collision.

6.3.2.3 General safety during user trials

The robot operates at relatively slow speeds to lessen the effects of undesired contact with the human user and other objects in the environment. In addition, the experimenter can press an emergency stop button to turn off the robot's power during a user delivery trial to avoid any unwanted contact.

6.3.3 The Behaviors

In this study, the experimenter chooses whether the robot will perform a direct or indirect delivery before the start of each trial. This could actually be inferred by the robot [70] or explicitly selected by the user, but we chose explicit direction by the experimenter to reduce the study's complexity. To start the trial, the experimenter hits a key on a keyboard of a remote computer connected to the robot's on-board computer through Wi-Fi. Next, the robot asks the user to supply a laser command. The user then shines the laser pointer control either at a location on or around him or herself (direct delivery) or at a location on a nearby table (indirect delivery).

The robot estimates the 3D location of the laser point in an ego-centric coordinate frame using the laser pointer interface. If the distance of the laser point is greater than 1.5m, the robot moves closer to the selected location and asks the user to repeat the laser command. Moving within 1.5m of the user selected location and repeating the laser command helps reduce the error in the robot's estimate of the location. We refer to the time from the start of the trial until the final laser command as the detection time (DT).

The robot then performs direct or indirect delivery depending on the type of trial

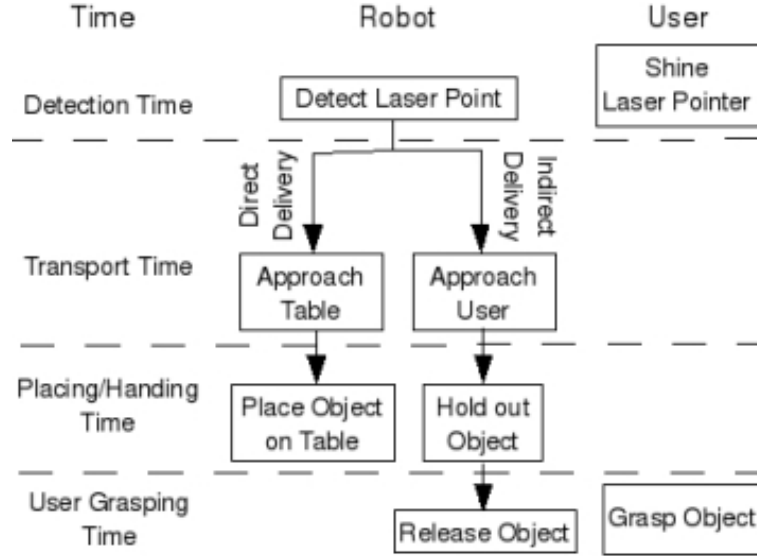


Figure 55: This figure shows the different time intervals, robot behaviors, and user actions involved in both direct and indirect delivery. Note that the user actions are identical for both delivery methods. Robot behaviors and user actions are shown in boxes.

that the experimenter chose. Figure 55 shows the behaviors that the robot executes for direct and indirect delivery, the actions that the human user performs during the trial, and the different time intervals that we measure and report in Section 6.4.

6.3.3.1 Direct delivery

After detecting a laser point within 1.5m, the robot turns to face the laser point, detects the user’s face with the stereohead and makes a 3D estimate of the location of the face. If the robot does not detect a face in a volume around the laser point, it stops and reports a direct delivery failure.

To detect faces, the robot first uses the Viola-Jones face detector as implemented in OpenCV to generate multiple face hypotheses for the left and right camera images independently. The robot then uses a Gaussian Mixture Model for skin color [105] trained on an online database of faces [37] to remove false positives from the Viola-Jones face detector. Finally, the robot triangulates each pair of remaining hypotheses from the left and right camera images to generate 3D face hypotheses. The robot

rejects 3D face hypotheses that are either smaller than 13cm or larger than 25cm, or are at a height of less than 1m or greater than 2.2m above the ground. The robot then selects the 3D hypothesis closest to the robot as the estimated location of the user's face.

After detecting the user's face, the robot approaches the user in a straight line path. It stops when it is either 1m from the user's face or it detects an obstacle, such as the user's feet, using the previously described safety screen.

Once the *Approach User* behavior as described above is completed, the transport time (TrT) ends and the robot executes the *Hold out Object* behavior. To do this, the robot uses the linear actuator to move the laser range finder 20cm below the estimated height of the face and rotates it so that it scans parallel to the ground. The robot then performs a 2D connected component labeling of the points in the resulting scan. When two points are less than 2cm from one another, they are considered to be connected. The robot then selects the connected component closest to itself as the user's body.

Let P_{face} be a 3-tuple representing the estimated 3D coordinate of the user's face and P_{body} be a 2-tuple representing the 2D coordinate of the centroid of the user's body in the planar scan. The coordinate of the direct delivery location is $(P_{body}[0] - 0.25m, P_{body}[1], P_{face}[2] - 0.25m)$ where the X axis points out from the robot, the Y axis is to the robot's left and the Z axis is vertical. This corresponds to a point backed off a quarter meter from the estimated body, laterally at the center of the estimated body, and below shoulder height. If possible, the robot then moves the manipulator so that the object is at this location. After holding out the object, the robot asks the user to grasp the object which marks the end of the placing/handing time (PHT).

Next, the robot monitors its force sensing fingers and releases the object after the user has grasped it. It adds the force vectors measured by both the force sensing

fingers to estimate the resultant force between the manipulator and the object. If the robot detects a change greater than 1.4N in the magnitude of this estimated resultant force, the robot releases the object, marking the end of the grasping time (GrT).

6.3.3.2 Indirect delivery

To deliver an object to a table, the robot moves toward the 3D location selected by the laser point, raises the laser range finder 20cm above this selected location, and takes a 3D scan with the tilting laser range finder. It performs a subset of this scan around the laser point to detect a flat surface and approaches the laser point in a direction normal to the boundary of this surface.

Once the robot is close to the flat surface it takes another 3D scan and uses this information to refine its estimate of the height of the surface. It then navigates such that the location for placement, specified by the laser pointer, is within the workspace of the robot's object placing controller.

After approaching the table, the transport time (TrT) ends and the robot executes the *Place Object on Table* behavior. It takes a 3D scan to determine if the object placing controller can operate without a collision and then executes it. More details about the flat surface detection algorithm and the object placing behavior can be found in [40]. After placing the object on the table the robot asks the user to grasp the object from the table. This marks the end of the placing/handing time (PHT). When the user successfully grabs the object, the grasping time ends (GrT). The end effectors have force torque sensors and detects the change of forces when a user grabs the object to record the grasping time.

6.3.4 Laser pointers

In the previous studies of user needs assessment and the first human evaluation, we found that currently available pen-type hand-held laser pointers have considerable usability problems for many ALS patients (see 56). Patients reported that these laser



Figure 56: Pen-type hand-held laser pointers

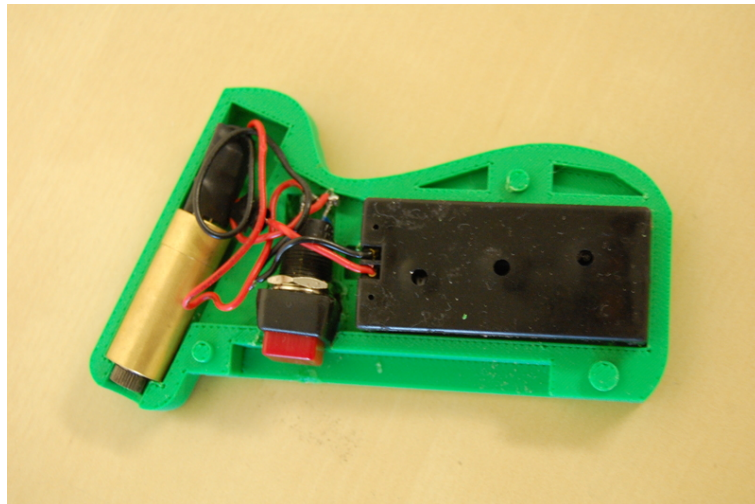


Figure 57: Components of the redesigned hand-held laser pointer

pointers were difficult to grasp because it is too thin and small, too heavy because most of them were steel-cased and included heavy batteries, and were hard to press the button because buttons were too small and it needs movement of the thumb. To address these issues, I designed and built a light-weight hand-gun type laser pointer by use of the SolidWorks 3D modelling software and uPrint 3D printer (see 58). Inside plastic casing made with a 3D printer, I arranged a commercially available laser diode unit, a battery package with 2 AAA batteries, and a trigger with a push button (see 57). In the previous human evaluation study, I created a ear-mounted laser pointer



Figure 58: Redesigned hand-held laser pointer

by attaching a laser diode unit to a commercially available bluetooth headset (see Figure 59). Although the participants of the study showed high satisfaction ratings of the ear mounted laser pointer, it had room for improvement too. The attached push button was too small and hard to press. The assembled unit was too heavy and it falls off from the ear often. As I designed the new hand-held laser pointer, I designed a new ear-mounted laser pointer with the same 3D modelling software and a 3D printer. I tried to minimize the weight of the laser pointer by using thin plastic casings and utilized a bigger push button available in a local office supply store.

6.4 *Methods*

We describe the methodology of this human evaluation beginning with participant recruitment. Next we describe the experimental design and setup. Lastly, we describe the procedure we performed for each trial.



Figure 59: The ear mounted laser pointer used in the previous study

6.4.1 Participants

We recruited eleven participants from the Emory ALS Center. Ten participants were ALS patients and one patient was diagnosed with PLS. Among the eleven patients, two patients participated in the previous evaluation study, and another patient previously experienced the use of the robot. The eight remaining patients participated in using the robot for the first time during this study. We contacted the two previous participants by telephone call and mail. We visited the Emory ALS clinic three times to recruit the first time participants. Table 25 shows the demographic information of these 11 participants.

As patient rounds were performed, a staff nurse or physician first asked patients whether they would be interested in participating in our study where some upper limb mobility is required. If the patient was interested, then one or two representatives from our research team explained the delivery capabilities of the robot as well as usage of the laser pointer interface. We emphasized that using the interface would require some squeezing or pressing ability with at least one hand, and that some arm movement would be required to grab the object from either a table or the robot itself. After a



Figure 60: Redesigned ear-mounted laser pointer

Table 25: Demographic information for all 11 patients

Variables	Values
Gender	Male (8), Female (3)
Ethnicity	White (10), African American (1)
Age	37 - 70 (average 60.1) years
Diagnosis	30.3 (average for all) 19.4 months ago (for 10 ALS patients)

Table 26: Demographic information for 8 later patients

Variable	Values
Gender	Male (6), Female (2)
Ethnicity	White (7), African American (1)
Age	37 - 70 (average 59.8) years
Diagnosis	34.9 months ago (average)

short question and answer period, the user then told us whether they were comfortable and interested in participating. We contacted the patient who participated in the previous evaluation study through mail and telephone communication and explained the hand and arm movements required to operate the robot in a similar fashion. We provided 50 US dollars to each patient as compensation for participation in the study.

Table 26 shows the demographic information for the 8 participants after we implemented safety measures to the ear-mounted laser pointer-E.

The population of individuals with ALS exhibit varying degrees of motor impairment ranging from limited hand gripping capability to paralysis below the neck. Thus, we do not claim that the group of participants in this evaluation study is a representative sample of the entire ALS population. We believe that object delivery assistance would be most useful for those with some level of upper limb and gripping capabilities. Accordingly, we did not include those with severe upper limb motor impairments in this study.

6.4.2 Experimental design

The independent variables of this study include the method of delivery (direct and indirect delivery) and the object type. We used the following three objects in this study: 1) a cordless phone, 2) a medicine bottle, and 3) a TV remote control with masses and dimensions as shown in Table 27. We selected these objects from the top four objects in the list of everyday objects prioritized by ALS patients described in [11]. We did not select the medicine pill (whose rank is #2 in the list) as one of the objects for this study due to manipulation limitations of the robot.

The quantitative dependent variables are detection time (DT), transport time (TrT), placing/handing time (PHT), user grasping time (GrT), and total time (TT), which are defined in Section 6.3. For qualitative measurement of the users' experiences, we conducted several surveys which we later describe in Section 6.4.4.5.

Each patient participated in eighteen object delivery trials using the robot. These trials consisted of all possible combinations of: the two delivery methods, three object types, and three repetitions ($2 \times 3 \times 3 = 18$ trials). We conducted the trials in a counter-balanced fashion.

For the purposes of this study, we assumed that the object have been already fetched and placed in the robot hand to reduce the task trial time and focus on the delivery portion of the task. This was considered to be a safe assumption, as we

Table 27: Mass and size of objects

Object	Mass	Length	Width	Height
Cordless phone	116 g	15.0cm	4.8cm	2.9cm
Medicine bottle	99 g	8.2cm	4.4cm	4.4cm
TV Remote	90 g	17.0	4.7cm	2.8cm



Figure 61: Experimental setup. The desk chair and table used in the experiment are shown in the bottom-left. The robot start positions are shown to the right.

had previously validated the grasping functionality of the robot, using different user control interfaces for commanding the robot, to detect, grasp, and lift objects off of the floor in a previous evaluation study [9].

6.4.3 Experimental setup

The study took place in a simulated living room environment with dimensions of $3.64\text{m} \times 4.4\text{m}$ (see Figure 61).

Participants were seated for the entire experiment. When participants brought their own wheelchair, they used it for the study. If they did not bring a wheelchair (e.g., used a walker), but used one at home, we provided a standard wheelchair for them to use for the experiment. For two participants who did not use a wheelchair in their daily lives, we provided a standard desk chair.

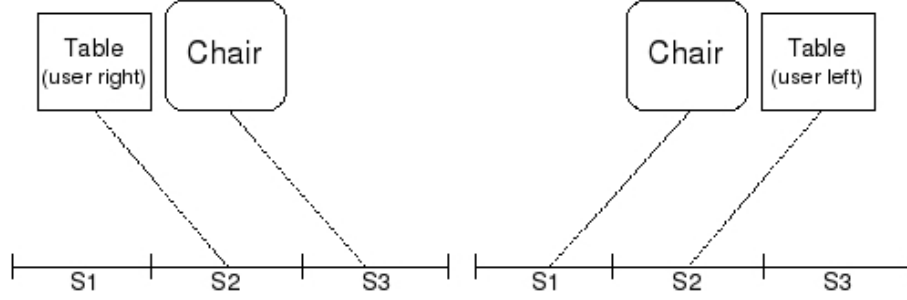


Figure 62: Left: Starting positions when the user prefers the table on his right. Indirect: S2, Direct: S3. **Right:** Starting positions when the user prefers the table on his left. Indirect: S2, Direct: S1.

For the indirect delivery method, we built a height-adjustable table combining a desk chair and rectangular coffee table in a customary manner to fit the size of the table to the experimental environment but the height of the table is comparable to those of commercially available kitchen tables (see 63). We placed the table adjacent to and at the height of the armrest of wheelchairs based on a United States standard [83]. We allowed the user to select the side on which the table was placed for the entire experiment, depending upon which side was more comfortable for the user to reach for an object on the table.

At a distance 2m away from the front face of the chair, we marked three robot initial positions (S1, S2, and S3) with tape on the floor. For indirect delivery trials, we placed the robot at the center position S2 and then it traveled along a diagonal path to place the object on the table to the side of the user’s choice (e.g., either user left or user right). As shown in Figure 62 (Left), if the user preferred the table to be on his right, then the robot started at position S3 for direct delivery. On the other hand, if the user preferred the table on his left, the robot started at position S1 for direct delivery.

This starting position scheme prevented the robot from approaching the user in a direct, frontal path. We took this precaution based on the previous finding by Walters and colleagues that reported a user preference for a robot approach from



Figure 63: A height adjustable table

the side during object delivery [98]. In addition, the scheme enabled the robot to approach the user at the same angle for both delivery methods.

6.4.4 Procedure

6.4.4.1 Initial paperwork

When a participant visited the lab, we welcomed him and asked him to be seated in either a wheelchair or a chair positioned as shown in Figure 62. They then read and signed the appropriate consent forms and completed a demographic survey.

6.4.4.2 Assessing motor capabilities of participants

Next, we asked which hand was more comfortable to use to pick up objects and then measured gross upper limb movement using a simplified task questionnaire as follows:

1. Can you place your hand behind your head?
2. Can you place your hand on top of your head?



Figure 64: The three objects used in this study: TV remote control, cordless phone, medicine bottle. (L to R)

3. Can you place your hand to your mouth?

These questions comprise a part of the Action Research Arm Test (ARAT) which clinicians use for assessment of upper arm functions [63]. Each item can have scores from 0 (no movement at all) to 3 (moved normally). The first task is the most difficult to perform and if it is given a score of 3, testing stops and the two other items are given a score of 3, resulting in a total score of 9. If the first score is less than 3, then the other two items are tested.

6.4.4.3 Selection of laser pointer

After the assessment, we introduced a hand-held laser pointer and an ear-mounted laser pointer as described in Implementation section, and asked the participant which would be more comfortable to use.

We created a method to determine to what extent in space a user could reach his arm out to grasp a object held in front of him. We will refer to this space as the *grasping workspace*. This information would help us better design the direct delivery task so that the robot could autonomously deliver an object to a reasonable

position in front of the user. In order to measure the *grasping workspace*, we created a measurement instrument as shown in Figure 65. It has a metal body frame with an arm that stretches out toward the user’s body which represents the Y-axis. Three positions along the Y-axis 8cm apart are marked with Velcro. To the Velcro, an L-shaped plastic frame can be attached at any of the three positions. Additionally, five positions along the frame are marked with Velcro 8cm apart relative to the floor and represents the Z-axis. The entire instrument can be picked up and moved by the experimenter 8cm to the left or right of the user and represents the X-axis. A piece of Velcro was attached to the medicine bottle and attached to various Velcro pieces on the *grasping workspace* measurement instrument. We asked each user to grab the medicine bottle placed at various X,Y,Z positions on the instrument. Trials were marked as successful if the user could reach out, grasp the bottle, and bring it back to their lap without dropping it, and unsuccessful otherwise. The force needed to remove the medicine bottle from the instrument is comparable to the force needed to remove the object from the robot during direct delivery.

6.4.4.4 *Delivery trials*

After the users completed all pre-task assessments, we explained the two object delivery methods. Then we asked the participant to practice using the laser pointer and conducted one trial run of each delivery method before the experiment began. Each participant conducted a total 18 trials as described in Section 6.4.2.

6.4.4.5 *Satisfaction surveys and final interview*

After a user completed a set of 6 direct and indirect delivery trials with one object, we administered a brief survey regarding their experience. The same survey was administered again after 6 trials were completed for the second object and then again for the third object. The survey contained the following statements which had response choices graded by a 7-point Likert scale from strongly disagree (1) to strongly agree



Figure 65: Instrument for measuring the *grasping workspace*.

(7):

Q1) I could effectively use the system to accomplish the given tasks.

Q2) It was not physically burdensome to use the system.

Q3) Overall, I was satisfied using the system.

When the user completed all the trials, we administered the final satisfaction surveys for direct and indirect delivery methods over their experiences with all three objects. The survey also used the same 7-point Likert scale:

Q1) I could effectively use the system to accomplish the given tasks.

Q2) I am satisfied with the time between I gave command and the robot delivered object.

Q3) It was easy to point with the interface.



Figure 66: **Top:** The user shines the laser point onto her lap, then the robot delivers the object directly to the user (direct delivery). **Bottom:** The user shines the laser point onto the table, then the robot delivers the object to the table (indirect delivery).

Q4) It was easy to learn to use the system.

Q5) It was not physically burdensome to use the system.

Q6) Overall, I was satisfied using the system.

After the final satisfaction survey, we conducted an interview to ask participants questions regarding their experience using the robot. Additionally, we used this time to gather suggestions for improving the technology. Specifically, we asked them about their preferred method by asking which delivery method they felt more comfortable using.

6.5 Results

All eleven participants reported their right hand as dominant and preferred the table to be placed on their right side. Although most participants showed some level of difficulty moving their arms and fingers, all of the participants were able to reach for and grasp objects from the robot gripper or from the tabletop. Seven out of eleven participants scored of nine out of nine for their gross arm movement test and eight out of eleven participants could reach all the positions measured for the *grasping workspace* test.

6.5.1 Implementation change during the study

After conducting trials with three users, we found a potentially critical problem. We observed that the robot tried to approach too close for some users. Although we successfully stopped the robot before collision on all occasions, we had to change the system design to accommodate the tilting laser finder to help avoid possible collision as described in the Implementation section. After the change, we conducted studies with 8 additional participants. As a result of this change in the implementation, robot performance was significantly degraded. For the sake of consistency and standardization, we only report analysis of quantitative performance measures from the last

Table 28: Gross arm movement score and grasping workspace

Subject ID	Gross movement	Grasping workspace	Difficulty in upper-limb movement
1	7	All reached	Difficulty in raising over shoulder
2	9	All reached	Difficulty in highest points
3	9	All reached	Couldn't use the thumb
4	9	All reached	Moved normally
5	5	Z5 difficult	Could raise hands up to the chest
6	9	All reached	Couldn't talk
7	9	All reached	Lower two fingers slightly weak
8	7	Z5 impossible	Lower two fingers were weak
9	7	Z5 impossible	Could raise to shoulder height
10	9	All reached	Could move but slow
11	8	All reached	Holding for long time was difficult
Mean	8		

eight sets of participant trials. With respect to the satisfaction survey and interviews, the data from the three previous participants was still valid. Thus, these results were included in the analysis and are reported in the following sections.

6.5.2 Quantitative performance measures

As previously mentioned, quantitative data analysis was performed on only the last eight patients' data. Following the code change to better implement the safety measures, there was a significant change of performance. Analysis of variance (ANOVA) was conducted using a general linear model to determine the effects of the two independent variables on the dependent variables. Statistical analysis showed that delivery method and object type do not have interaction effects with each other, which enables us to separately analyze the effects of these two independent variables. Additionally, further analysis revealed that object type does not have a significant effect on any of the time measures. Thus, we can focus on analyzing the differences caused by the delivery method alone. The delivery method had significant effects on TrT , PHT, and TT with p-values of less than 0.001. However we found no significant

Table 29: Mean times by delivery method in seconds

Method	Detection (DT)	Transport (TrT)	Placing/ Handing (PHT)	Grasping (GrT)	Total (TT)
Direct	13.76	89.33	30.94	1.2	135.3
Indirect	12.17	183.93	65.8	1.6	263.6
Overall	12.9	141.89	50.3	1.4	206.6

effect on times which required user interaction: DT (p-value of 0.084) and GrT (p-value of 0.109). Table 29 shows comparisons of the means of each time measurement by object type. Overall, indirect delivery was significantly slower than direct delivery. Direct delivery was only slightly slower in detection time, but the difference was not significant. The significant differences in task time between direct and indirect delivery method was caused by additional laser scanning required for indirect delivery. In indirect delivery, EL-E had to perform comprehensive laser scanning to determine the position of edge of the table. We also programmed so that EL-E rotates itself to align in perpendicular to the edge of the table. These additional steps made the indirect delivery method much slower than direct delivery and future modification of implementation could reduce the task time. For time measurement, Indirect delivery was slower than Direct delivery in total time with significant difference. Direct delivery took more in detection time but the difference was not significant. In short, direct delivery was faster. However, I found no significant difference between three objects. I conducted a non-parametric statistical test of Mann-Whitney to compare the success rates of two delivery methods. The delivery success rate was significantly higher for indirect delivery (p-value was less than 0.01) with 98% success rate (70 out of 72 trials) than for direct delivery with 78% success rate (56 out of 72 trials), while the overall success rate was 88% (126 out of 144 trials). These results include nine direct delivery failures for one particular participant. In short, indirect delivery was more robust.

6.5.3 Failed trials

Eighteen failures were observed in 144 total trials. Two of the failures occurred during indirect delivery, while the remaining sixteen occurred during direct delivery trials. One of the indirect delivery failures was due to a laser detection failure which occurred when the user was using the ear-mounted laser pointer. When the user turned his head to the right in order to shine the laser point onto the table, a portion of the hooded shirt the user wore obstructed the laser beam, causing it to split into two laser points. One laser point shone on the user and the other on the table. The robot detected the laser point on the user’s body, which caused us to stop the trial. In the second case, the robot failed to release the object after attempting to place it on the table.

Fifteen of the sixteen failures occurring during direct delivery trials were due to the same flaw of the direct delivery implementation. The failures occurred when the robot estimated a direct delivery location outside its workspace after observing a connected component that was relatively close to the robot. Nine of these failures occurred with one user who had a relatively large torso which explains the source of the close connected component. The other six instances of this failure occurred with three other users and we expect that the users’ posture and size may have been involved, but have not been able to determine the exact causes. The other direct delivery failure occurred when the force torque sensors stopped providing readings possibly due to a server communication error.

6.5.4 Satisfaction survey

The questions used to assess participant satisfaction were previously discussed in Section 6.4.4.5, as shown in Tables 30 and 31. As shown in Table 30, all participants expressed high levels of satisfaction close to “strongly agree” (a score of 7). For all three questions, the average satisfaction scores did not differ much by delivery method

Table 30: Mean satisfaction by object and method

Method / Object	Q1	Q2	Q3
Handing-over	6.69	6.64	6.83
Placing-on	6.92	6.78	6.94
Phone	6.79	6.71	6.87
Medicine Bottle	6.79	6.71	6.79
TV Remote	6.81	6.71	7.00
Total	6.82	6.71	6.89

Table 31: Mean overall satisfaction by method

Method	Q1	Q2	Q3	Q4	Q5	Q6
Handing-over	6.82	5.55	6.55	6.91	6.82	6.82
Placing-on	6.82	5.45	6.64	7.00	6.82	6.91
Total	6.82	5.50	6.59	6.95	6.82	6.86

or by object type. Similarly, the overall satisfaction scores shown in Table 31 did not differ much by delivery method either. However, we note that the satisfaction score of Question 2: “I am satisfied with the time between I gave command and the robot delivered object” was below 6 which is lower than the other questions. This effect is likely to be a result of the slow performance of the robot.

6.5.5 Final interview

Analysis of the subjective results for all 11 participants was conducted on the assumption that the overall impression of users interaction with the robot should not vary considerably based on the changes in the safety measures. Thus, we included this data from the initial three participants. During the final interviews, we asked users whether they thought the robot was useful for object delivery and all the participants gave positive answers. All participants agreed that the robot gave enough feedback on its progress through its speech output mechanism. However, one participant thought the speech was difficult to understand. Most participants indicated that they did not have any difficulty using the laser pointer, although one user felt that the hand-held laser pointer grip was insufficient. Some participants wanted the hand-held laser pointer to be bigger and easier to squeeze, while one participant who

used the ear-mounted laser pointer wanted it to hook onto the ear more securely.

To compare the preference of delivery methods, I asked which delivery method they felt more comfortable using. Five participants chose indirect delivery, five preferred direct delivery and the one remaining participant indicated both methods were equally comfortable. Participants who preferred indirect delivery said that it gave them more flexibility in when and in what manner they grabbed the object. Several users slid their hand and arm along the table surface to grab the object. Participants who preferred direct delivery said that it required less arm movement to reach the object for grasping. Interestingly, none of the participants who preferred direct delivery said that the speed of delivery was the reason they preferred this method, despite the fact that direct delivery was much faster than indirect delivery. One participant said he preferred indirect delivery because of the 9 failures he experienced with direct delivery as described in Section 6.5.3.

Additionally, one participant experienced difficulty with direct delivery because the object was obstructed by the robot gripper which made it difficult for him to grasp the object. He suggested that the robot grasp only one end of the object to make it easier for him to retrieve from the robot. Another participant experienced difficulty using the laser pointer when the laser light was incidentally blocked by and reflected on his clothing. Other suggestions to improve direct delivery included bringing the object closer to the user and improving the speed of delivery. No participants reported difficulty using the indirect delivery method. For the laser pointer interface, one participant complained that it needs to be bigger but 10 other did not raise any concerns.

6.6 *Discussion and conclusion*

The results of this study illustrate that the robot was able to accomplish the delivery task with an overall 88% success rate. Although the success rate was high for indirect



(a)



(b)



(c)



(d)

Figure 67: Posture and body size variation. (a) and (d) show more reclined postures. (b)-(d) show varying wheelchair foot rest heights and extensions.

delivery (98%), we observed a relatively high failure rate in the direct delivery condition. We have plans to address the various causes of the failed trials to improve the robustness of the direct delivery procedure. Specifically, for direct delivery, we will implement changes to allow the robot to back up and re-try the *hold out object* behavior in the event a close connected component is detected. While indirect delivery was more reliable, it was much slower because it required additional laser scanning procedures to detect the edge of the table.

As illustrated by the results of the satisfaction surveys and final interviews, participants showed very high levels of satisfaction regarding the robotic delivery methods. However, we found less favorable responses regarding the time it took to complete the delivery tasks. We also found that the preferences of delivery methods were equally divided. The preferences were mostly related to the manner in which the user could comfortably and successfully grab the object. Indirect delivery provided users with greater flexibility in the manner and time of grabbing the object, while direct delivery reduced the arm movement needed to grab the object. The apparent differences in task time did not affect users' preferences of delivery methods.

With the current system, we believe that robust, autonomous delivery of objects to flat surfaces is achievable. Although user preferences were divided, delivery to flat surfaces showed very high satisfaction ratings and all participants were able to reach and grasp an object in every trial. This indicates that functional robotic assistance might be provided prior to fully solving some of the complex issues related to autonomous direct delivery. In contrast, further research will be required to ensure successful direct delivery by accommodating the large variations we encountered in posture and body size. This is a particularly significant issue with motor-impaired individuals who can be more vulnerable to robotic error and can have more varied postures due to both physical weakness and variability in the design of wheelchairs (see Figure 67). After analyzing the causes of the failure cases, we are confident that

we can deliver solutions to the problems related with varying postures and body size. Once a suitable solution has been implemented, providing direct delivery in addition to indirect delivery would be beneficial to some users with motor impairments who prefer the efficiency and comfort of direct delivery. Additional possibilities would be to create an additional delivery mechanism that would allow the robot to hold out an object, allowing the user to approach the robot to grasp it, or for the robot to place the object on an attached tray and present the tray to a user. Given our results and the many options available, we are confident that object delivery will not be a limiting factor for future assistive robots.

CHAPTER VII

CONTRIBUTION

7.1 *Research contribution*

The thesis research contributed to the state of academic knowledge and research methodologies in the following 4 areas.

7.1.1 Understanding the needs of ALS patients and other people with motor impairments

The needs assessment study provided both immediate and interesting information regarding the changes needed in the design of the robot, including the end effector/gripper design, the robot's mobility, and the controlling interface. All of this information will be helpful for directing the future design and development efforts for the assistive robot system. We hope these results help other researchers in the field of assistive robotic manipulation to develop technologies to help individuals with motor impairments achieve relative independence in their daily lives.

7.1.2 Identifying relative importance of everyday objects for robotic object retrieval

A key question for robotic researchers focused on manipulation in domestic environments is: *What objects are important to manipulate?* Within this thesis, I have provided one answer to this question, conditioned on a specific application and user population. We have proposed a ranked list of 43 everyday objects to be used for the evaluation of assistive mobile manipulation systems operating in domestic settings. We have used methods of user-centric design to create and validate this list with a group of severely motor impaired individuals, ALS patients. The progressive nature of ALS makes this disease a good representation of varying degrees of motor

impairments. By developing benchmarks tailored to specific application domains and user populations, researchers have the opportunity to ground their research and answer the otherwise subjective question: *What is important?*. Moreover, we believe benchmarks of this nature can enable researchers without direct access to target user populations to contribute to progress based on a validated foundation.

7.1.3 Improvement of assistive robot design through user feedback

The user studies helped to illustrate how each interface design could be improved. The hand-held laser pointer was heavy and the button was difficult to press and hold for some participants. One participant noted that the button of the ear-mounted laser pointer was difficult to press and a larger button would be preferred. Participants also suggested that using a trackball or joystick to control the touch screen or rearranging the buttons would increase its ease of use and controllability during one-handed use. Based on these suggestions, I redesigned a hand-held laser pointer and an ear-mounted laser pointer. Although we did not conduct a formal user study to compare the usability of old and new designs of laser pointers, we found that users in the second human evaluation utilizing the redesigned laser pointers reported fewer usability problems during the experiment compared to the first human evaluation.

One participant experienced difficulty in direct delivery because the object was obstructed by the robot gripper which made it difficult for him to grasp the object. He suggested that the robot should grasp only one end of the object to make it easier for him to grasp. Another participant experienced difficulty using the laser pointer when the laser light was incidentally blocked by and reflected on his clothing. Other suggestions to improve direct delivery included bringing the object closer to the user and improving the speed of delivery. No one reported difficulty using the indirect delivery method. For the laser pointer interface, one participant complained that it needs to be bigger but ten other participants did not raise any concerns.

7.1.4 Validation of the robot’s effectiveness for assisting ALS patients

The experimental results of the human evaluation phase 1 study demonstrate El-E’s usefulness for acquiring objects to meet the needs of prospective users. All three interfaces were effective for the object manipulation task with an overall success rate of 94.8%. Although no participant had previous experience with robots like El-E, all participants were able to operate the robot with any of the three interfaces in less than 10 minutes, which suggests that the robot was easy to use for the prospective users.

The results of the human evaluation phase 2 study show that the robot could accomplish the delivery task with an overall 88% success rate. Although the success rate was high for indirect delivery (98%), we observed a relatively high failure rate in the direct delivery condition. As found in the results of the satisfaction surveys and final interviews, participants showed very high levels of satisfaction regarding the robotic delivery methods. However, we found less favorable responses regarding the time it took to complete the delivery tasks. This problem represents an area for further investigation.

7.2 *Publication*

The results of this proposed research are likely to be of interest to three major academic fields: human-computer interaction, robotics, and assistive technologies. The list of publications accomplished during the thesis research includes:

ASSETS 2008 Laser Pointers and a Touch Screen: Intuitive Interfaces for Autonomous Mobile Manipulation for the Motor Impaired, Young Sang Choi, Cressel Anderson, Jonathan D. Glass, and Charles C. Kemp, ACM SIGACCESS Conference on Computers and Accessibility, 2008 [9]

This paper discusses the results of the user study on object fetching.

ICORR 2009 Benchmarking Assistive Mobile Manipulation: A List of Household Objects for Robotic Retrieval Prioritized by People with ALS, Young Sang Choi, Travis Deyle, Tiffany Chen, Jonathan Glass, Charles C. Kemp, International Conference on Rehabilitation Robotics (ICORR 2009), 2009 [11]

This paper discusses the results of the needs assessment and object prioritization study.

IEEE RO-MAN 2009 Hand It Over or Set It Down: Object Delivery with an Assistive Mobile Manipulator, Young Sang Choi, Tiffany Chen, Advait Jain, Cressel Anderson, Jonathan Glass, Charles C. Kemp, 18th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN 2009, (accepted)[10]

This paper discusses the results of the second user study on object delivery.

AAAI Spring Symposia 2009 Human-Robot Interaction Studies for Autonomous Mobile Manipulation for the Motor Impaired, Young Sang Choi, Cressel Anderson, Travis Deyle, Charles C. Kemp, AAAI 2009 Spring Symposia, Technical Report SS-09-03 [12]

This paper discusses the results of the needs assessment and the user study on object fetching, primarily focusing on the study methodology and experimental design.

7.3 *Presentations*

Tenth international ACM SIGACCESS Conference on Computers and Accessibility

Halifax, Nova Scotia, Canada, October 15, 2008

presentation, “Laser Pointers and Touch Screen: Intuitive Interfaces for Autonomous Mobile Manipulation for the Motor Impaired”

INFORMS Annual Meeting Washington DC, October 12, 2008

presentation, “Understanding User Needs in Developing an Autonomous Manipulation Robot to Help the Motor Impaired”

AAAI Spring Symposium: Experimental Design in Real World Applications

Palo Alto, California, March 25, 2009

presentation, “Human-Robot Interaction Studies for Autonomous Mobile Manipulation for the Motor Impaired”

Guest Lecture Introduction to Cognitive Science, CS/ISYE/PSYC/PST 3790, Spring 2009, Georgia Institute of Technology

lecture title, “Human Studies for Assistive Mobile Manipulation Robots”

APPENDIX A

IRB DOCUMENTS

A.1 Abstract

An Assistive Robot to Fetch Everyday Objects for People with Severe Motor Impairments

BACKGROUND: Persons who develop severe motor impairments, such as amyotrophic lateral sclerosis (ALS) and Parkinsons disease, experience a sharp decline in their quality of life as they lose their ability to perform everyday tasks independently. In face of the mounting strain of their condition, many of them find relief through the employment of persons to assist in fulfilling their everyday needs. However, this approach is both costly and limited as an assistant may be in attendance only for a few hours out of a day. We believe that the creation of an assistive robot that can retrieve everyday objects and perform simple manipulations for persons with severe motor impairments will greatly decrease their dependence on others and thus increase their quality of life.

METHODS: 25 subjects, both male and female, with amyotrophic lateral sclerosis will be interviewed using a set of open-ended questions as well as the Revised Amyotrophic Lateral Sclerosis Functional Rating Scale (ALSFRS-R). These interviews will be used to determine which tasks will need to be performed most frequently by the robot, which tasks are most important for the robot to perform, and how the robot should behave while carrying out a task and after the task has been completed. To further establish these areas of interest, we will also ask that each subject complete a take home survey, which consists of a log of items dropped by each subject. Photographs of each object should be included in the take home survey but not contain

any identifying material which puts subjects at risk. As the prototype robot will be implemented, we will conduct user testing with subjects in which they perform tasks of object retrieval using the robot.

A.2 Consent form for human evaluation phase I

Georgia Institute of Technology

Project Title: An Assistive Robot to Fetch Everyday Objects for People with Severe Motor Impairments

Principal Investigator: Charlie Kemp

Department: HSI

Purpose

You are being asked to be a volunteer in a research study. The purpose of this study is to increase the quality of life in persons with severe motor impairments, such as persons with amyotrophic lateral sclerosis, through the development of an autonomous robot that fetches everyday objects selected by a user.

Procedures

If you decide to be in this study, your participation will involve the completion of the Revised Amyotrophic Lateral Sclerosis Function Rating Scale and a demographic information sheet. You will be asked to record the incidents of dropped or unreachable objects in your daily life for about a week. You will be asked interview questions on how you interact with everyday objects and caregivers. The interview may repeat one more time with separation of about a month. In addition, you will be asked to use an assistive robot in testing sessions. You may visit the research facility or be visited by the research team. Testing sessions may be held maximum of two times. You may be recorded by audio, video, and/or photograph. The video or photograph may be used in the publication of the results. The audio, video, and/or photograph will be destroyed after the analysis is done which is within one year after they are

taken. Additionally, some basic experimental data may be collected during the study. All acquired data will be maintained in a secure location that will be accessible only to the study researchers. Your participation for each interview and testing session should require approximately one to two hours. Your maximum participation time will be eight hours over a seven month period.

Risks/Discomforts

There are no significant risks or discomforts related to participation in this study. The risks/discomforts of this study are no greater than those possible during your daily life. Benefits The following benefits to you are possible as a result of being in this study: Your participation in this research may not benefit you directly. Potential benefit to others may result from the knowledge in the user needs and user experiences of the assistive robot gained from your participation in this research study. Compensation to You There is no monetary compensation for your participation but you will be paid for parking and transportation for the purpose of participation if you provide proof of payment. Confidentiality The following procedures will be followed to keep your personal information confidential in this study: The data that is collected about you will be kept private to the extent allowed

A.3 Consent form for human evaluation phase II

Georgia Institute of Technology

Project Title: An Assistive Robot to Fetch Everyday Objects for People with Severe Motor Impairments

Principal Investigator: Charlie Kemp

Department: HSI

Purpose

You are being asked to be a volunteer in a research study. The purpose of this study is to increase the quality of life in persons with severe motor impairments, such

as persons with amyotrophic lateral sclerosis (ALS, also know as Lou Gehrigs disease), through the development of an autonomous robot that manipulates everyday objects selected by a user. About 20 subjects are expected to participate in the study as an estimate.

Procedures

If you decide to be in this study, your participation will involve the completion of the Revised Amyotrophic Lateral Sclerosis Function Rating Scale and a demographic information sheet. You will be asked to use an assistive robot in testing sessions performing tasks such as picking up and retrieving objects. In the experiment, you will be asked to fill out a survey and be asked a set of interview questions. You may visit the research facility or be visited by the research team. You may be asked to participate in a second round of testing at a later date. You may be recorded by video, and/or photograph. The video or photograph may be used in the publication or presentation of the results. We will keep the video or photograph in a secure place for potential future research. Additionally, some basic experimental data such as performance time, error, and satisfaction may be collected during the study. All acquired data will be maintained in a secure location that will be accessible only to the study researchers. Your participation for each testing session should require approximately two hours.

Risks/Discomforts

There are no significant risks or discomforts related to participation in this study. The risks involved are no greater than those involved daily activities such as preparing a meal. Benefits Your participation in this research may not benefit you directly. Potential benefit to others may result from the knowledge gained from your participation in this research study. Compensation to You You will be compensated at \$50 for 2 hours of participation for each testing session. Should there be a second testing session, you will be compensated \$50 for 2 hours of participation for the second testing

session. If you elect to participate for only a portion of the study, your compensation will be pro-rated accordingly.

APPENDIX B

STUDY MATERIAL

B.1 ALSFRS-R

Revised Amyotrophic Lateral Sclerosis Function Rating Scale (ALSFRS-R)

SUBJECT ID: Date:

QUESTIONS:

a. Speech

4 = Normal speech processes

3 = Detectable speech disturbances

2 = Intelligible with repeating

1 = Speech combined with nonvocal communication

0 = Loss of useful speech

b. Salivation

4 = Normal

3 = Slight but definite excess of saliva in mouth; may have nighttime drooling

2 = Moderately excessive saliva; may have minimal drooling

1 = Marked excess of saliva with some drooling

0 = Marked drooling; requires constant tissue or handkerchief

c. Swallowing

4 = Normal eating habits

3 = Early eating problems occasional choking

2 = Dietary consistency changes

1 = Needs supplemental tube feeding

0 = NPO (exclusively parenteral or enteral feeding)

d. Handwriting

4 = Normal

3 = Slow or sloppy; all words are legible

2 = Not all words are legible

1 = Able to grip pen but unable to write

0 = Unable to grip pen

e. Cutting Food and Handling Utensils (patients without gastrostomy)

4 = Normal

3 = Somewhat slow and clumsy, but no help needed

2 = Can cut most foods, although clumsy and slow; some help needed

1 = Food must be cut by someone, but can still feed slowly

0 = Needs to be fed

Cutting food and Handling Utensils (alternate scale for patients with gastrostomy)

4 = Normal

3 = Clumsy but able to perform all manipulations independently

2 = Some help needed with closures and fasteners

1 = Provides minimal assistance to caregivers

0 = Unable to perform any aspect of task

f. Dressing and Hygiene

4 = Normal function

3 = Independent and complete self-care with effort or decreased efficiency

2 = Intermittent assistance or substitute methods

1 = Needs attendant for self-care

0 = Total dependence

g. Turning in Bed and Adjusting Bed Clothes

4 = Normal

3 = Somewhat slow and clumsy, but no help needed

2 = Can turn alone or adjust sheets, but with great difficulty

1 = Can initiate, but not turn or adjust sheets alone

0 = Helpless

h. Walking

4 = Normal

3 = Early ambulation difficulties

2 = Walks with assistance

1 = Nonambulatory functional movement only

0 = No purposeful leg movement

i. Climbing Stairs

4 = Normal

3 = Slow

2 = Mild unsteadiness or fatigue

1 = Needs assistance

0 = Cannot do

j. Breathing

4 = Normal

3 = Shortness of breath with minimal exertion (e.g., walking, talking)

2 = Shortness of breath at rest

1 = Intermittent (e.g., nocturnal) ventilatory assistance

0 = Ventilator dependent

k. Dyspnea

4 = None

3 = Occurs when walking

2 = Occurs with one or more of the following: eating, bathing, dressing

1 = Occurs at rest, difficulty breathing when either sitting or lying

0 = Significant difficulty, considering using mechanical respiratory support

l. Orthopnea

4 = None

3 = Some difficulty sleeping at night due to shortness of breath, does not routinely use more than two pillows

2 = Needs extra pillow in order to sleep (more than two)

1 = Can only sleep sitting up

0 = Unable to sleep

m. Respiratory Insufficiency

4 = None

3 = Intermittent use of BiPAP

2 = Continuous use of BiPAP during the night

1 = Continuous use of BiPAP during the night and day

0 = Invasive mechanical ventilation by intubation or tracheostomy

B.2 Structured Interview for Needs Assessment

An Assistive Robot to Fetch Everyday Objects for People with Severe Motor Impairments

Subject ID: Date:

Drop Frequency

1. On a daily basis, how often do you drop objects? () times a day () times a week () times a month

2. What objects do you drop most frequently?

3. Do you ever experience tremors? Yes / No a. If yes, how frequently? b. Do they ever cause you to drop objects?

4. Do you ever experience increased/sudden stiffness or weakness in your arms or hands? Yes / No a. If yes, how frequently? b. Does this ever cause you to drop objects?

Object Identity

5.Of the objects you drop, which do you find most important to retrieve? (e.g. a cell phone is more important than a pencil)

6.Are there any objects that you avoid using out of fear of dropping them? What objects?

7.Are there any everyday tasks that you can no longer do or have difficulty performing? What tasks? (e.g. open a door, flip a light switch, get a cup of water from a dispenser)

Location Identities

8.In order to avoid impeding your mobility, what distance is required from objects and people?

9. Are there specific places that people stand or objects get placed that make maneuvering more difficult than others?

10.How useful would it be for you if the robot can follow you in your room?

a.Not useful at all

b.Not much useful

c.Neither useful nor useless

d.Slightly useful

e.Very useful

11.How useful would it be for you if the robot can follow you to other rooms at your place?

a.Not useful at all

b.Not much useful

c.Neither useful nor useless

d.Slightly useful

e.Very useful

12.How useful would it be for you if the robot can open the door to move to another room?

- a. Not useful at all
- b. Not much useful
- c. Neither useful nor useless
- d. Slightly useful
- e. Very useful

13. How useful would it be for you if the robot can be transported to other place in your travel?

- a. Not useful at all
- b. Not much useful
- c. Neither useful nor useless
- d. Slightly useful
- e. Very useful

Method of Return

14. A caregiver is returning an object to you. What is the most convenient way for you to receive the item? (e.g. hold it out at a certain height or deposit the item in you lap)

15. A caregiver is placing an object on a surface rather than returning it to you. What locations are most accessible to you for the retrieval of objects? Height?

16. Between a caregiver returning an object to you or placing objects in an accessible location, which is more valuable to you?

- a. Caregiver returning / placing in an accessible location

Use of Laser Pointer

17. How familiar are you with laser pointers?

- a. Familiar
- b. Slightly unfamiliar
- c. Neither unfamiliar or familiar
- d. Slightly familiar

- e. Very familiar
18. Try to use a laser pointer. Can the person hold the pointer? Yes / No
19. Can the person point the dropped object? Yes / No
20. How comfortable are you using a laser pointer?
- a. Uncomfortable
 - b. Slightly uncomfortable
 - c. Neither uncomfortable or comfortable
 - d. Slightly comfortable
 - e. Very comfortable
21. Is there an easier way for you to point out objects in your surroundings than using a laser pointer (besides speech)?
- Acceptable Performance
22. How much error rate in object retrieval task would be acceptable for you? (%)
23. How long time for the task would be acceptable for you? (minutes)
24. How long learning time for the task would be acceptable for you? (hours)
- Other Questions
25. Is there someone available to help you with daily chores? Yes / No
- a. If yes, who?
26. Would a robot capable of retrieving objects be valuable to you? Yes / No
27. How much money would you like to spend for a robot helping you retrieve dropped objects?
28. Do you have any specific devices/instruments to help interact with objects, of your own creation or otherwise? For example, a tong?
21. Can you imagine a task which you want a robot to help you accomplish?

B.3 Human Evaluation Phase I

B.3.1 Pre-task questionnaire

A. Computer experience

1. How many years have you been using personal computers?
2. How many hours do you use a personal computer per a week?

B. Physical limitations

1. Do you have difficulty in moving one or both arms? Both: Left: Right:
2. Can you comfortably hold and point with a standard laser pointer?
3. Do you have difficulty in rotating and raising/lowering your head? Notes

B.3.2 Satisfaction survey for interface type X

1. I could effectively use the system to accomplish the given tasks.
2. I am satisfied with the time between you gave command and the robot detect object.
3. I am satisfied with the total time between you gave command and the robot finally picked up the object.
4. It was easy to find an object with the interface
5. It was easy to point an object with the interface.
6. It was easy to learn to use the system.
7. It was not physically burdensome to use the system.
8. Overall, I was satisfied to use the system.

B.3.3 Post Task Interview

A. Robot

1. Do you think the robot is useful for object pick-up?
2. Did you have enough feedback on the progress of the robot?

B. Interfaces

3. Overall, which interface do you prefer to use and why?

	X = 0	X = 1	X = 2
Z = 0			
Z = 1			
Z = 2			
Z = 3			
Z = 4			

4. Did you have any difficulty in using the laser pointer interface?
5. Compared with standard laser pointer, was the head mounted laser pointer more comfortable?
6. Do you have any idea to improve the laser pointer interface?
7. Did you have any difficulty in using the touch screen interface?
8. Do you have any idea to improve the touch screen interface?

B.4 Human Evaluation Phase II

B.4.1 Pre-task assessment

A. Gross movement

1. Which hand / arm is more comfortable to use, the left or right?

CIRCLE ONE: LEFT RIGHT

2. Can you place hand behind your head?
3. Can you place hand on top of your head?
4. Can you place hand to your mouth?

B. Laser pointer

1. Which of the hand-held and ear-mounted laser pointer is more comfortable to use?

C. Grasping workspace

Insert a V for success. Insert a X for not success. Insert a Δ "or reaching but not grabbing" Y = 0

Y = -1

Y = 1

B.4.2 Satisfaction survey for direct delivery for object N

Delivery method A

- 1.I could effectively use the system to accomplish the given tasks.
- 2.It was not physically burdensome to use the system.
- 3.Overall, I was satisfied using the system.

B.4.3 Overall satisfaction survey

- 1.I could effectively use the system to accomplish the given tasks.
- 2.I am satisfied with the time between I gave command and the robot delivered object.
- 3.It was easy to point with the interface.
- 4.It was easy to learn to use the system.
- 5.It was not physically burdensome to use the system.
- 6.Overall, I was satisfied using the system.

B.4.4 Post Task Interview

A. Robot

- 1.Do you think the robot is useful for object delivery?
- 2.Did the robot give you enough verbal feedback on its progress?

B. Interfaces

- 3.Did you have any difficulty using the laser pointer interface?
- 4.Do you have any ideas to improve the laser pointer interface?

C. Delivery

- 1.Which delivery method did you feel more comfortable using?

CIRCLE ONE: DIRECT INDIRECT

2. Did you have any difficulty using the direct delivery method (delivery to your hand)?

3. Do you have any ideas to improve the direct delivery method?

4. Did you have any difficulty using the indirect delivery method (delivery to the table)?

5. Do you have any ideas to improve the indirect delivery method?

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VITA

I was born in Suwon city, Kyung-gi province, Republic of Korea, in 1974. I received my bachelor's and master's degrees from the Department of Industrial Engineering at Seoul National University in 1997 and 1999, respectively. During my masters work, I studied manufacturing information system and developed a 3D product information system on the World Wide Web. For the next five years, I worked for Samsung Electronics as a research engineer developing embedded software applications, including mobile web browsers. During my doctoral study in the School of Industrial and Systems Engineering at the Georgia Institute of Technology, I studied the ecology of accessible technology and designed and evaluated user interfaces for the control of an assistive manipulation robot. Throughout these diverse experiences, I have pursued a consistent goal of applying computing technology to benefit the quality of human life. To reach this goal, I have focused on health as the most important aspect of human life. My approach to research focuses on the application of human-computer interaction and human-machine systems.